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Introduction to Neutrino Physics

Pedro A. N. Machado

Jun/2017

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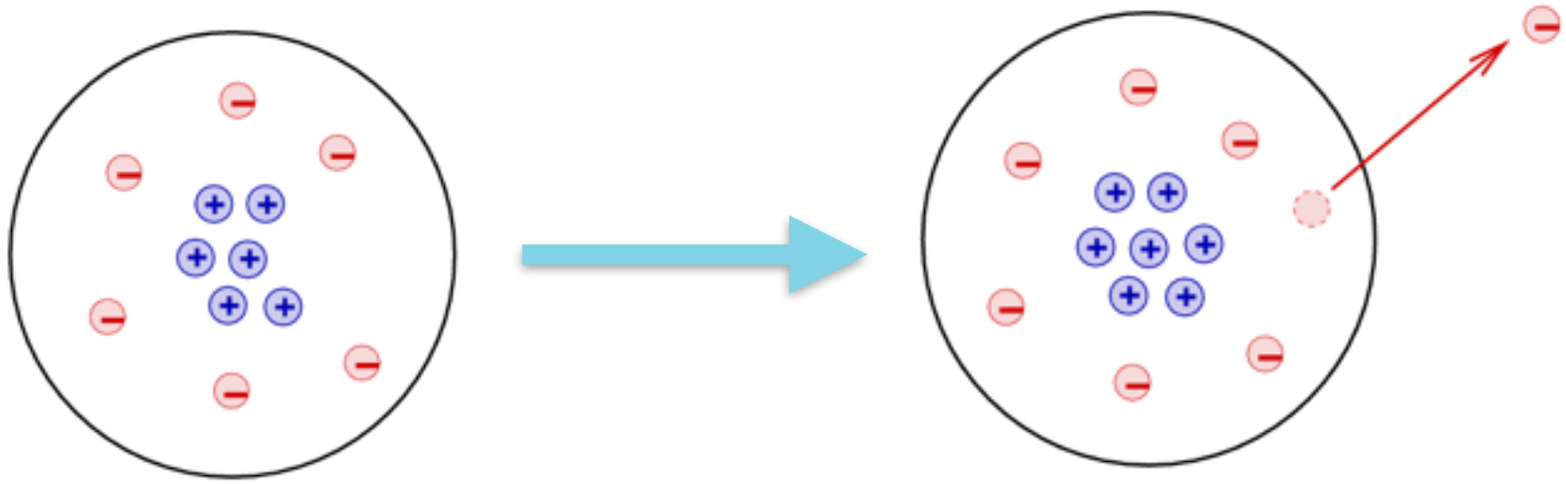

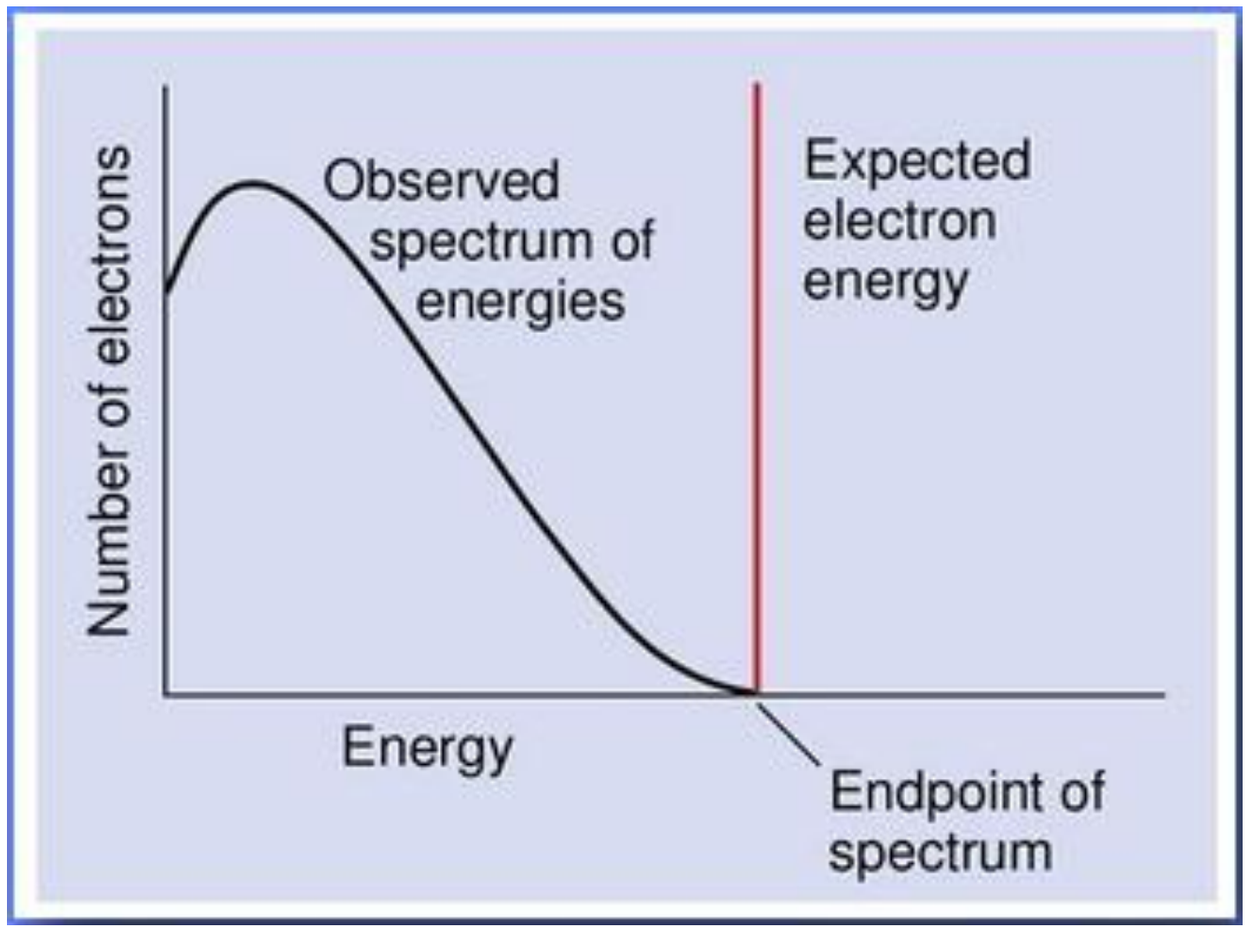

Observations by Sir J. Chadwick, 1914

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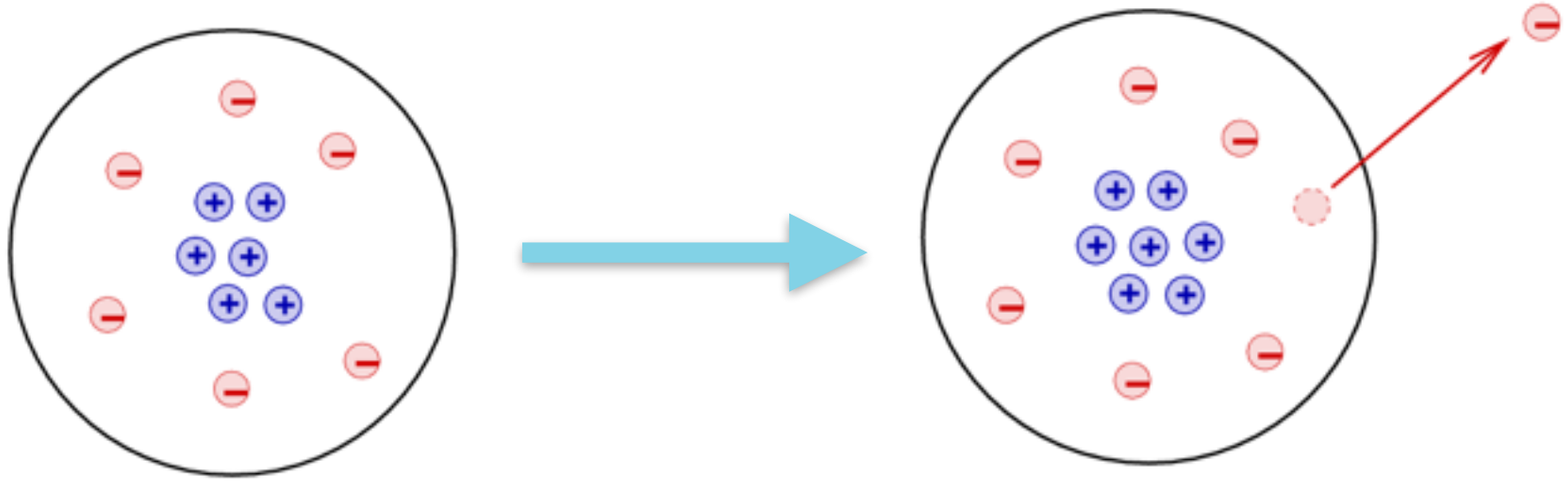
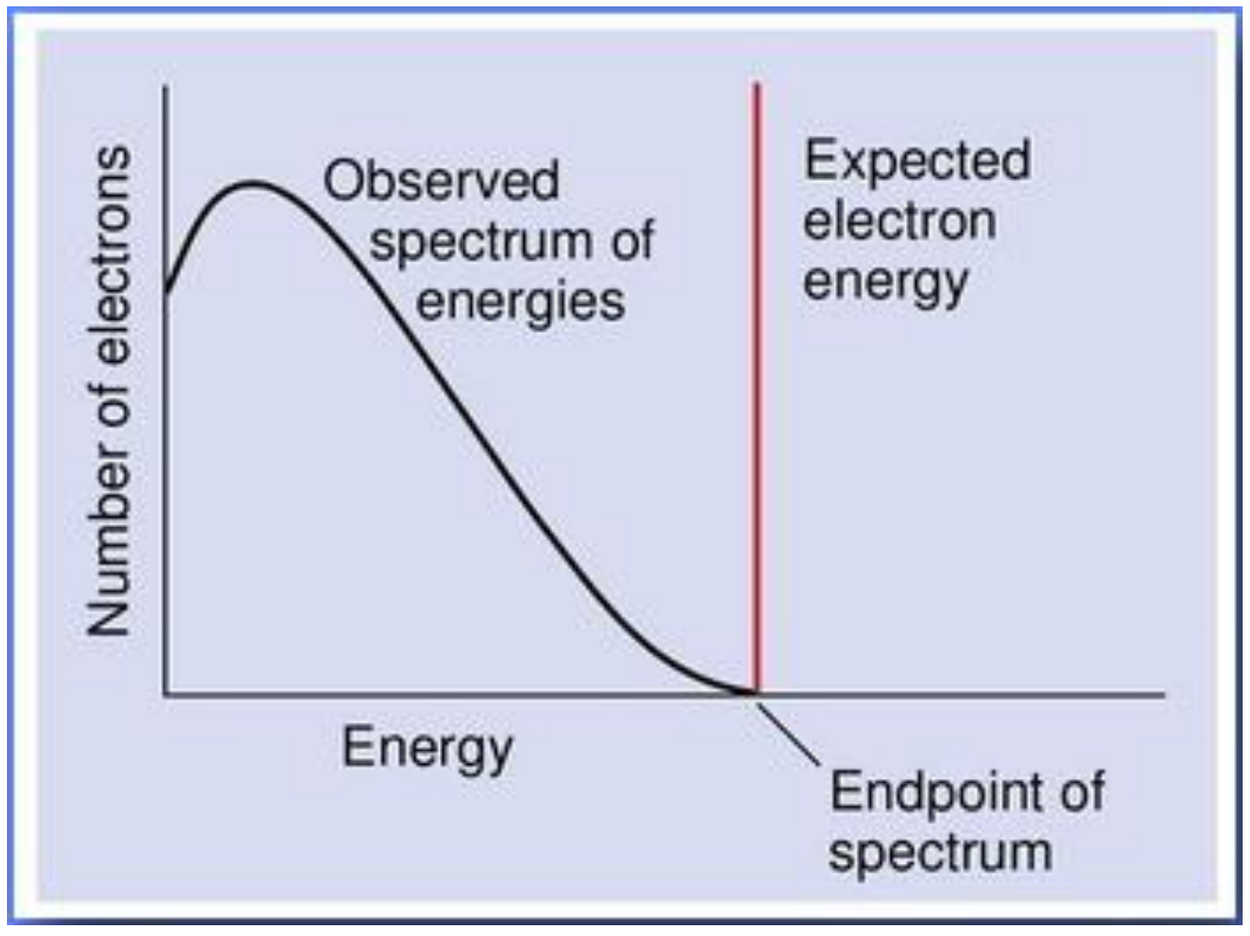
Pauli's Facebook profile picture





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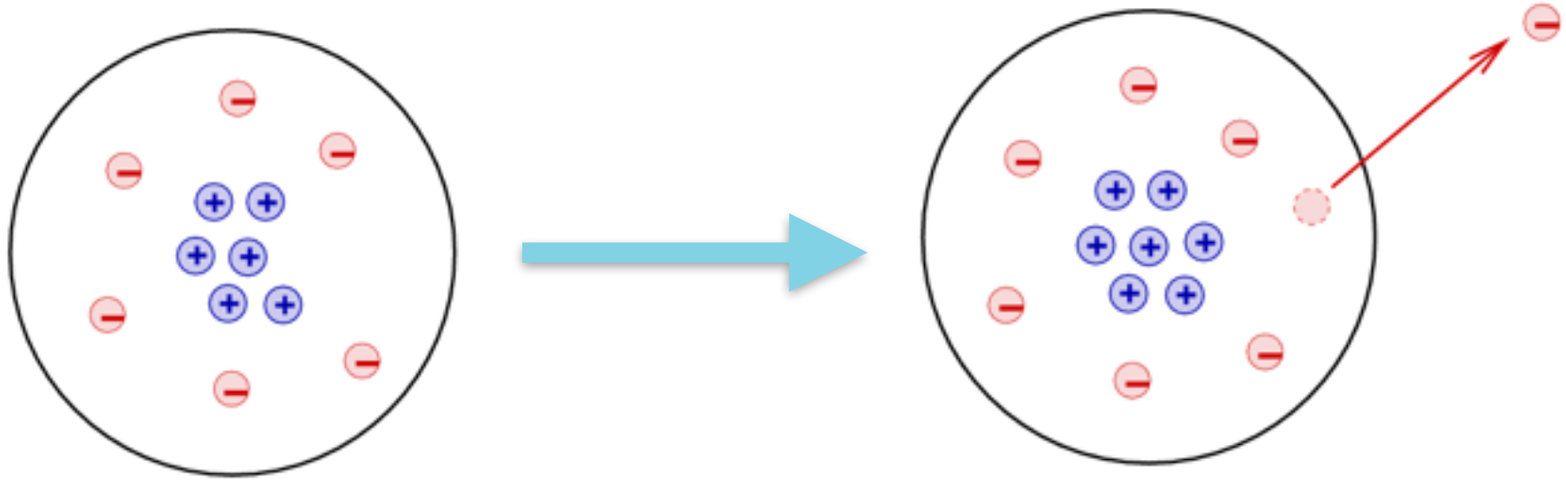


Winter of 1930

Original - Photocopie of PLC 0393

Abschrift/15.12.30 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

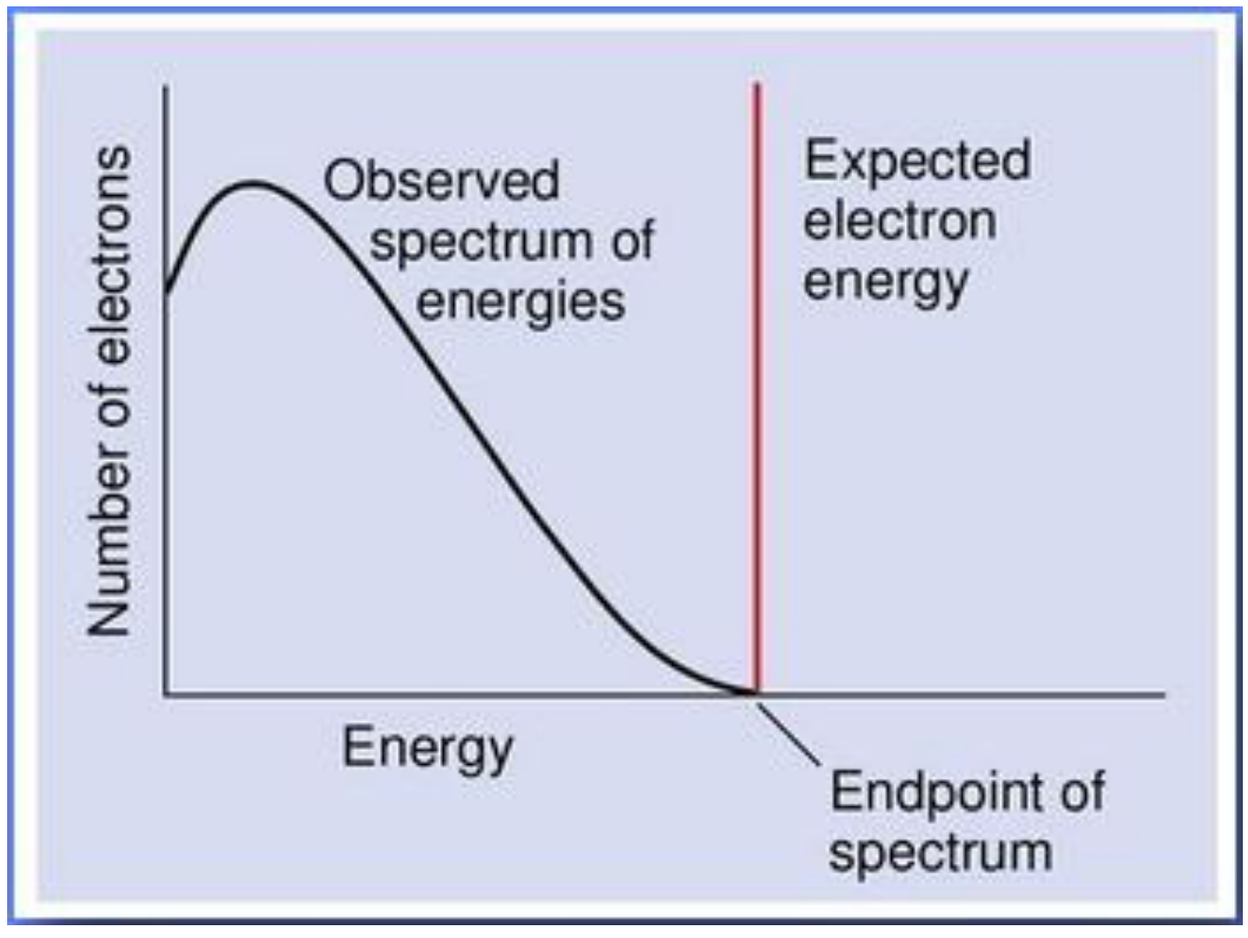
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



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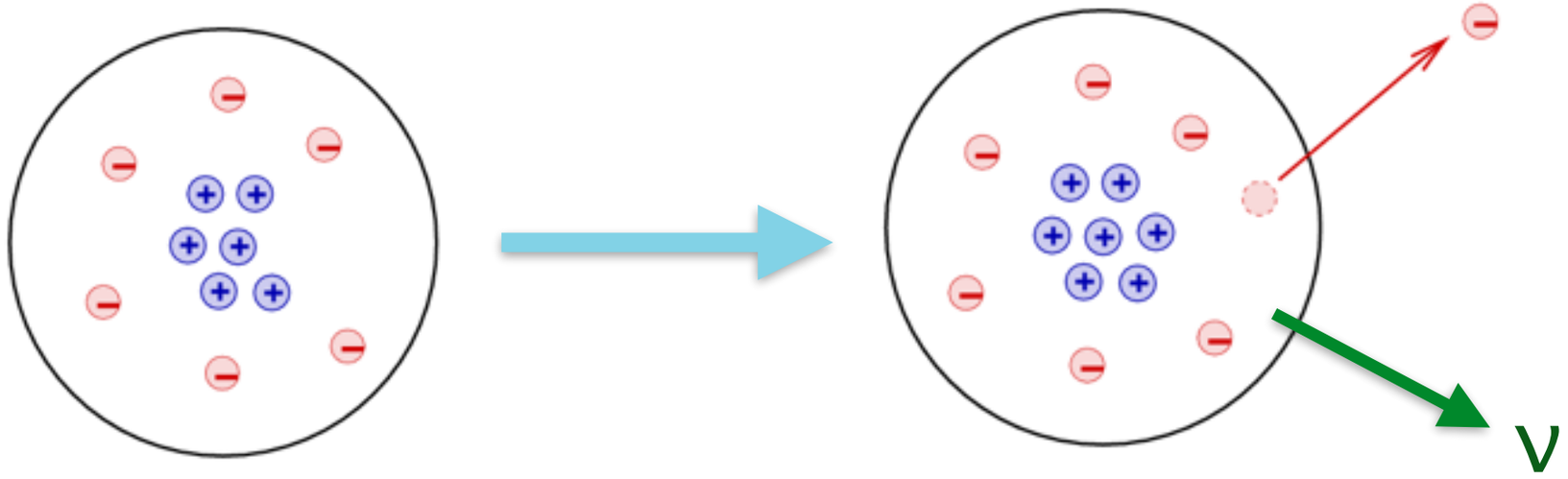

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- Gross violation of energy-momentum conservation!
- Postulates an "invisible" particle to avoid catastrophe - the **neutrino**

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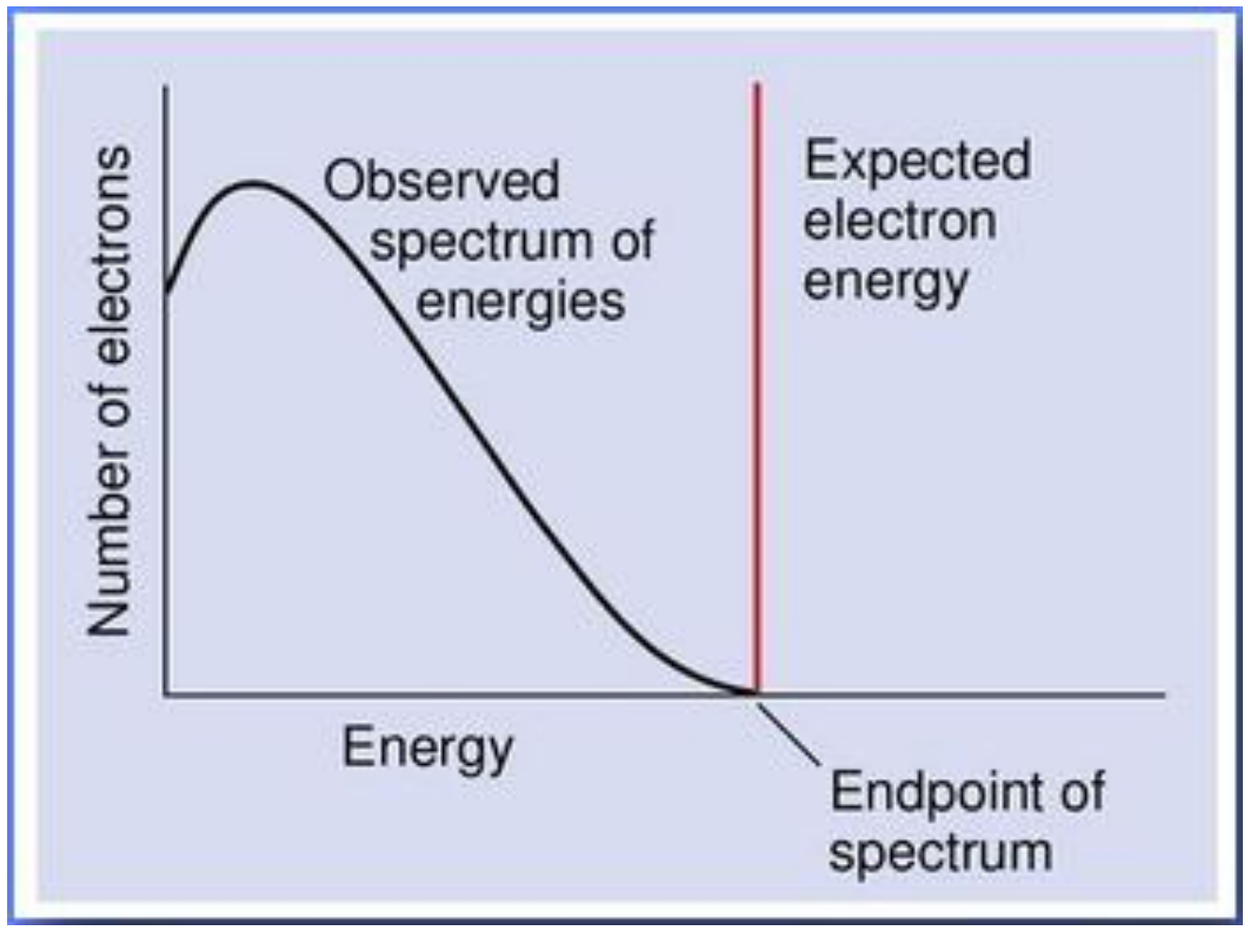

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The discovery of the neutrino: Cowan-Reines experiment, 1956

Fred Reines Clyde Cowan

Los Alamos NATIONAL LABORATORY EST. 1943

Savannah River Plant would provide a flux of $\sim 10^{13}$ ν/cm²/s

$$\bar{\nu} + p \longrightarrow n + e^{+}, \text{ then } n + {}^{108}Cd \longrightarrow {}^{109}Cd + \gamma$$

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Savannah River Plant would provide a flux of ~ 10^{13} ν/cm²/s

$$\bar{\nu} + p \longrightarrow n + e^{+}, \text{ then } n + {}^{108}Cd \longrightarrow {}^{109}Cd + \gamma$$

1995 Nobel prize for the detection of the neutrino

The discovery of the muon neutrino: Lederman, Schwartz and Steinberger, 1962

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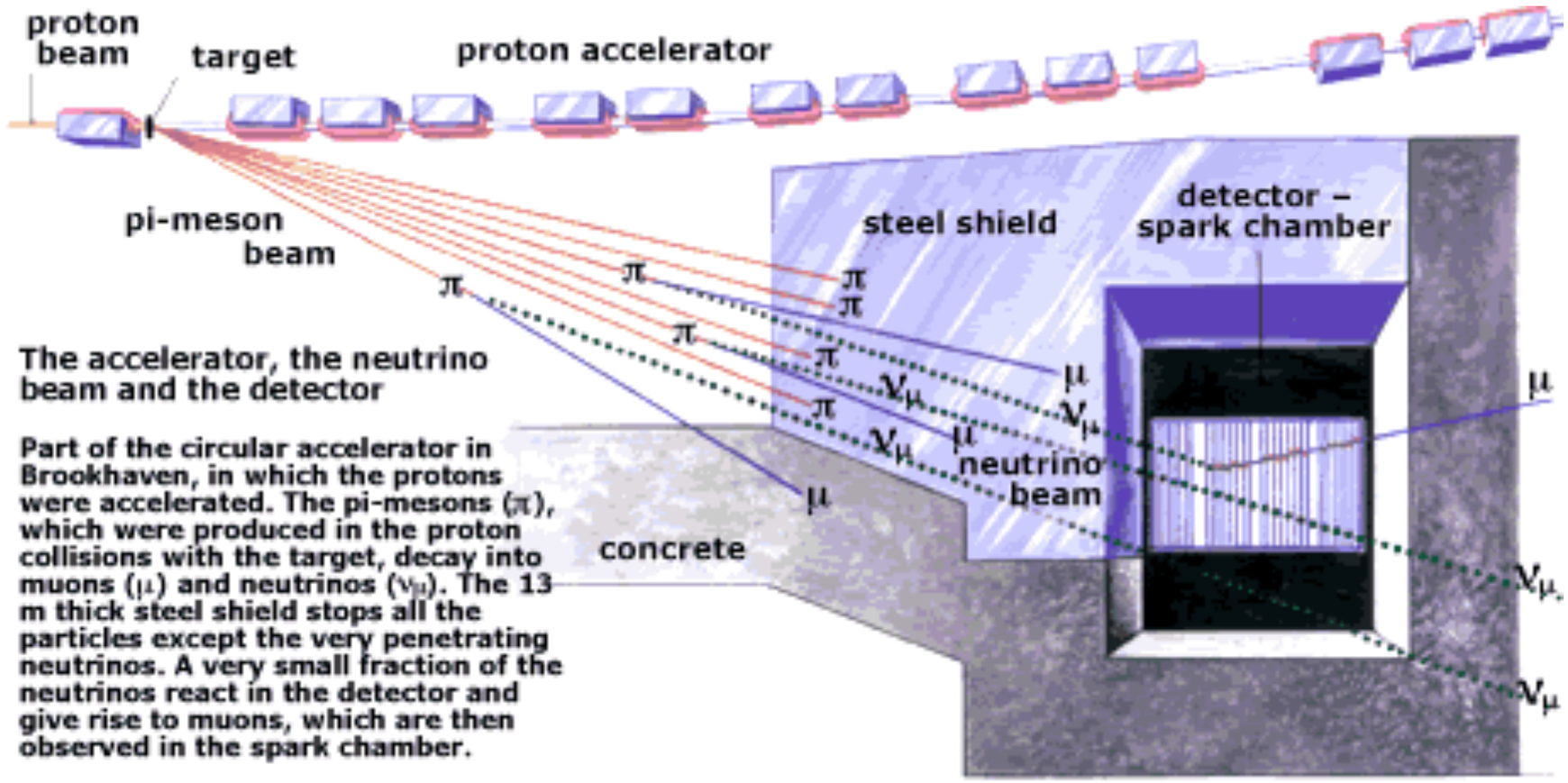

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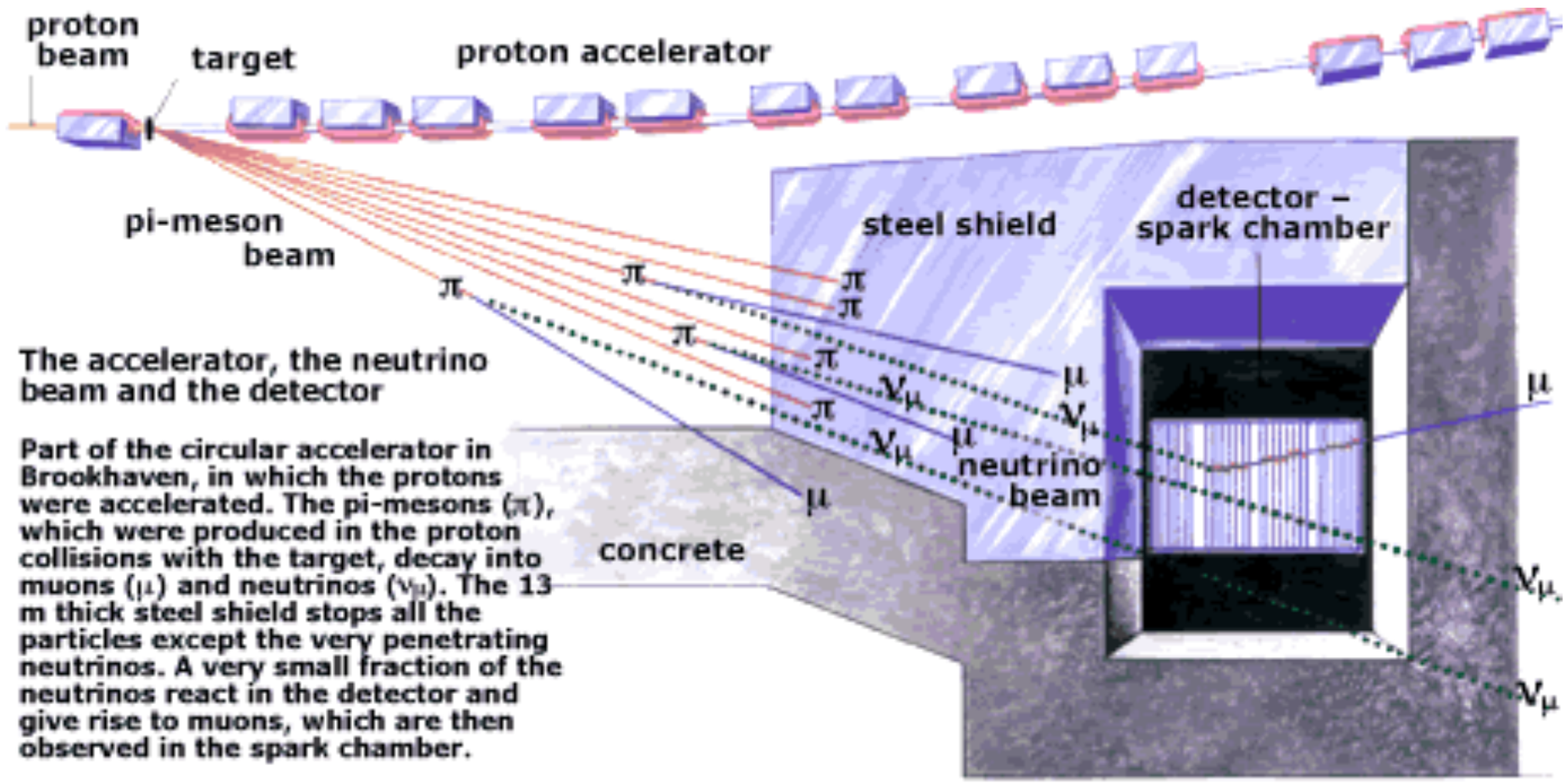

1988 Nobel prize for the neutrino beam method and the demonstration of the doublet structure of leptons through the discovery of the muon neutrino

The discovery of the tau neutrino:
The DONUT experiment, 2000

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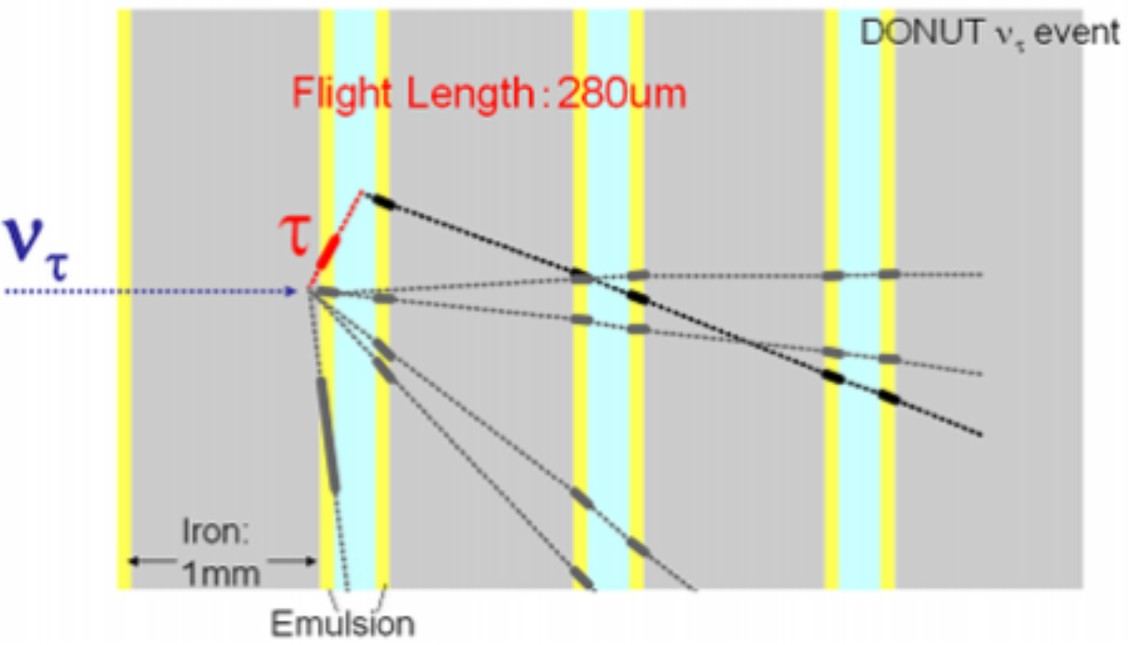
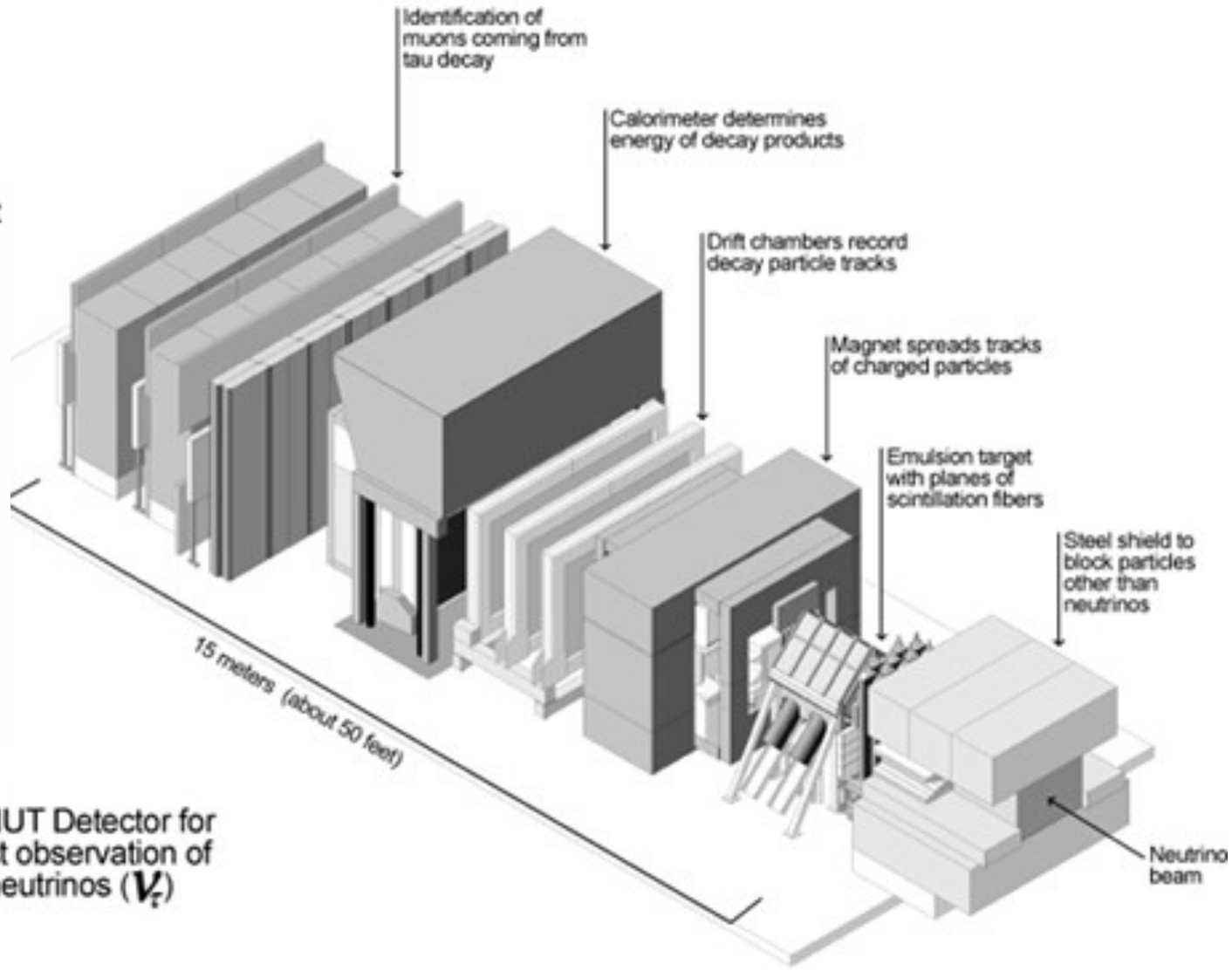




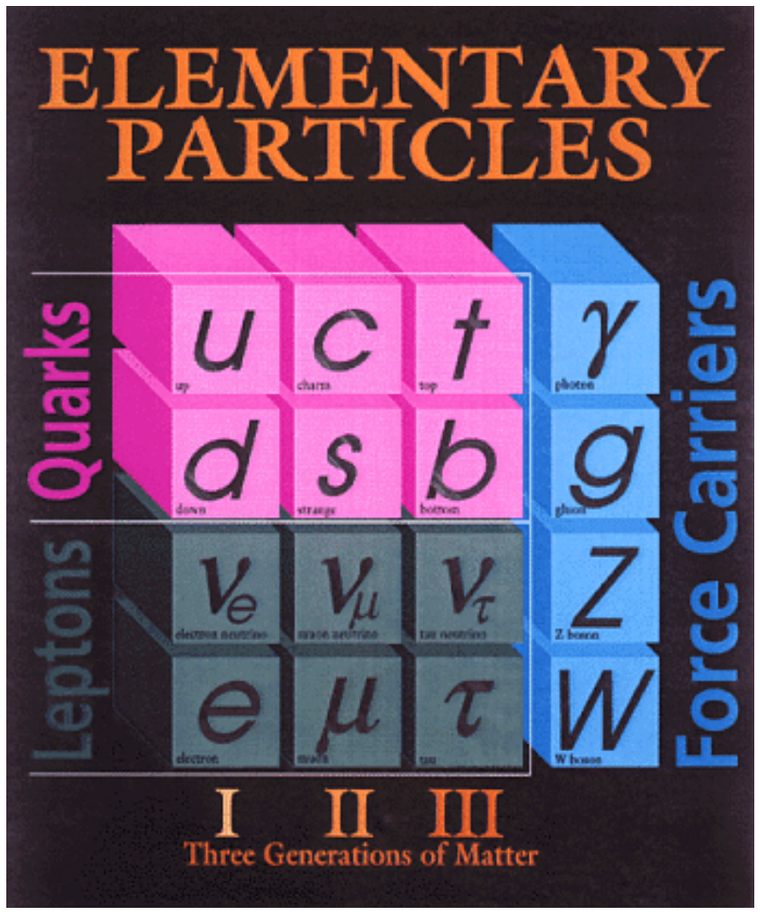
DONUT Detector for direct observation of tau neutrinos (ν_τ)

The Standard Model: the big picture

Fermions come in 3 families: identical except for their masses

4 fundamental forces:

- Strong: quarks
- Electromagnetic: quarks and charged leptons
- Weak: all fermions
- Gravity: anything



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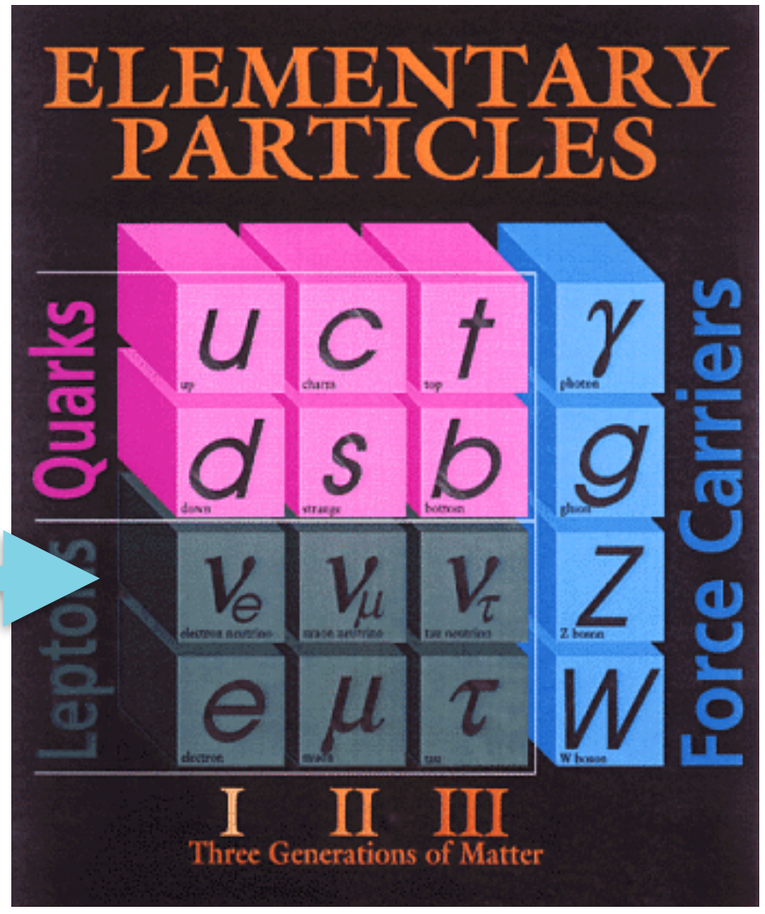
Focus on neutrinos,
particularly neutrino oscillations



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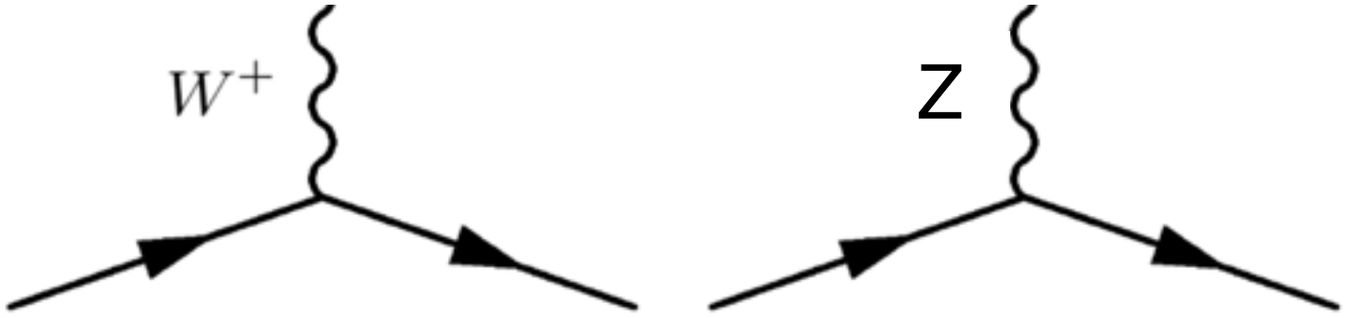
Before studying neutrino oscillations
we need to understand the structure of weak interactions

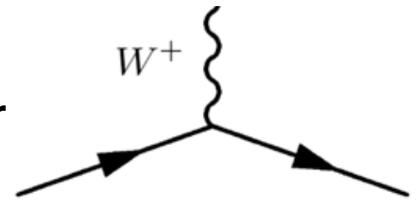


Weak interactions

$$\sum_{i=1}^{3} \bar{Q}_{Li} \not{p} Q_{Li} = \sum_{i=1}^{3} \frac{g}{\sqrt{2}} \left(\bar{u}_{Li} \gamma^{\mu} d_{Li} W_{\mu}^{+} + \text{h.c.} \right) + \ldots$$

Weak interactions

In the interaction basis, this interaction is diagonal in flavor



The “interaction" basis:

$$\sum_{i=1}^{3} \bar{Q}_{Li} \not{D} Q_{Li} = \sum_{i=1}^{3} \frac{g}{\sqrt{2}} \left(\bar{u}_{Li} \gamma^{\mu} d_{Li} W_{\mu}^{+} + \text{h.c.} \right) + \ldots$$

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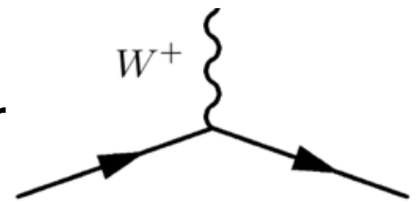

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Here, the masses do not need to be diagonal:

$$\sum_{i,j=1}^{3} y_{ij} \bar{Q}_{Li} \tilde{H} u_{Rj} \to \bar{\mathcal{U}}_L \cdot \mathbf{M}_u \cdot \mathcal{U}_R = \bar{\mathbf{u}}_L \cdot (V_L^u)^\dagger \cdot \mathbf{M}_u \cdot V_R^u \cdot \mathbf{u}_R$$

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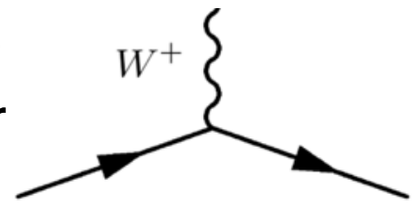

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quarks in mass basis (masses are diagonal)

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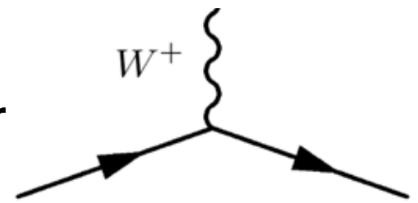

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quarks in mass basis (masses are diagonal)

$$\sum_{i,j=1}^{3} y_{ij} \bar{Q}_{Li} H d_{Rj} \to \bar{\mathcal{D}}_L \cdot \mathbf{M}_d \cdot \mathcal{D}_R = \bar{\mathbf{d}}_L \cdot (V_L^d)^\dagger \cdot \mathbf{M}_d \cdot V_R^d \cdot \mathbf{d}_R$$

Weak interactions

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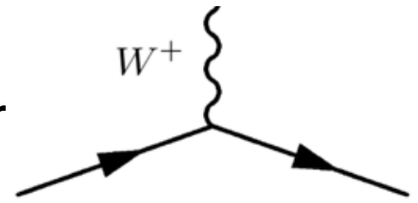

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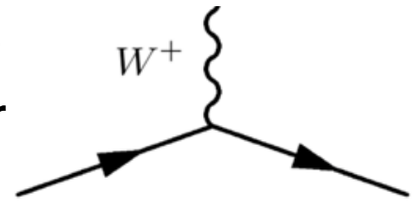

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A physical down quark can be produced in association with an up, charm or top quark!

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Weak interactions

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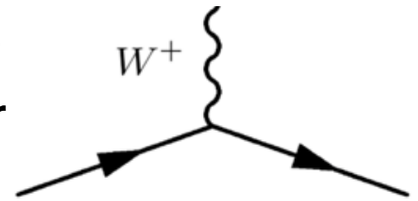


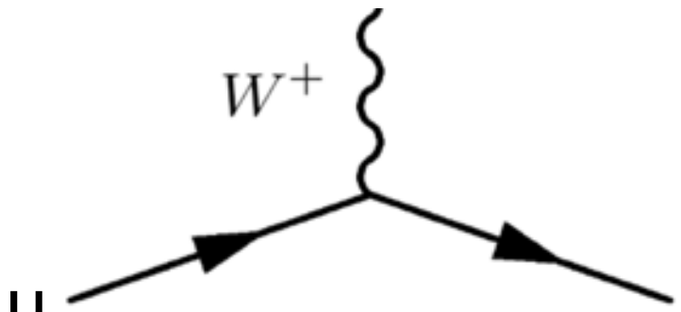
The “interaction" basis:

$$\sum_{i=} \ldots$$

Fermion states that have a well defined mass can have mixing under weak interactions!

The “ma

$$\sum_{i=1}^{3} \ldots + \ldots$$



superposition of d, s, b

A physical down quark can be produced in association with an up, charm or top quark!

Weak interactions

Same thing happens to neutrinos

(with one additional complication: we do not know the mechanism that generates neutrino masses!)

Neutrino Oscillations

$|\nu_\alpha\rangle$ Interaction eigenstate (produced by weak interactions)

$|\nu_i\rangle$ Mass eigenstate (eigenstate of the Hamiltonian)

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$$\mathcal{H}|\nu_i\rangle = E_i|\nu_i\rangle$$

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}|\nu_i\rangle$$

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i \qquad \text{Field } \psi \text{ annihilates state } |\psi\rangle$$

$$|\nu_\alpha\rangle = \nu^\dagger_\alpha|0\rangle = \sum_i \nu^\dagger_i U^*_{\alpha i}|0\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

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After producing a neutrino in a well defined flavor, it evolves like

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^{n} U^*_{\alpha i}|\nu_i(t)\rangle$$

We also detect it in a defined flavor, so the amplitude we measure is

$$A_{\alpha\beta}(t) = \langle\nu_\beta|\nu_\alpha(t)\rangle$$

Neutrino Oscillations

$$A_{\alpha\beta}(t) = \langle \nu_\beta | \nu_\alpha(t) \rangle$$

$$A_{\alpha\beta}(t) = \sum_{i=1}^{n} \sum_{j=1}^{n} U^*_{\alpha i} U_{\beta j} \langle \nu_j | \nu_i(t) \rangle$$

Neutrino Oscillations

$\hbar = c = 1$

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The Hamiltonian is related to the time evolution operator, so

$$|\nu_i(t)\rangle = e^{-i\,E_i t} |\nu_i(0)\rangle$$

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Neutrinos are relativistic (E,p >> m)

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p + \frac{m_i^2}{2E}$$

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$$= e^{-ipt} U^*_{\alpha i} U_{\beta i} \exp\left(-i \frac{m_i^2 t}{2E}\right)$$

Isolated an overall phase
Got lazy and stopped writing the sums
Used orthogonality condition:

$$\langle \nu_j | \nu_i \rangle = \delta_{ij}$$

Neutrino Oscillations

$\hbar = c = 1$

Let's isolate another overall phase

$$A_{\alpha\beta} = e^{-i(pt+m_1^2 t/2E)} U^*_{\alpha i} U_{\beta i} \exp\left(-i\frac{\Delta m^2_{i1} t}{2E}\right)$$

Neutrino Oscillations

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To make it simpler, consider two neutrinos
(two flavor framework, say ν_e and ν_μ)

$$U = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

Neutrino Oscillations

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Easy to explicitly show that

$$P(\nu_\mu \to \nu_e; L) = |A_{\mu e}(L)|^2 = 4c_\theta^2 s_\theta^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Substituted t by L (c=1)
There is only one Δm^2

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Neutrino Oscillations

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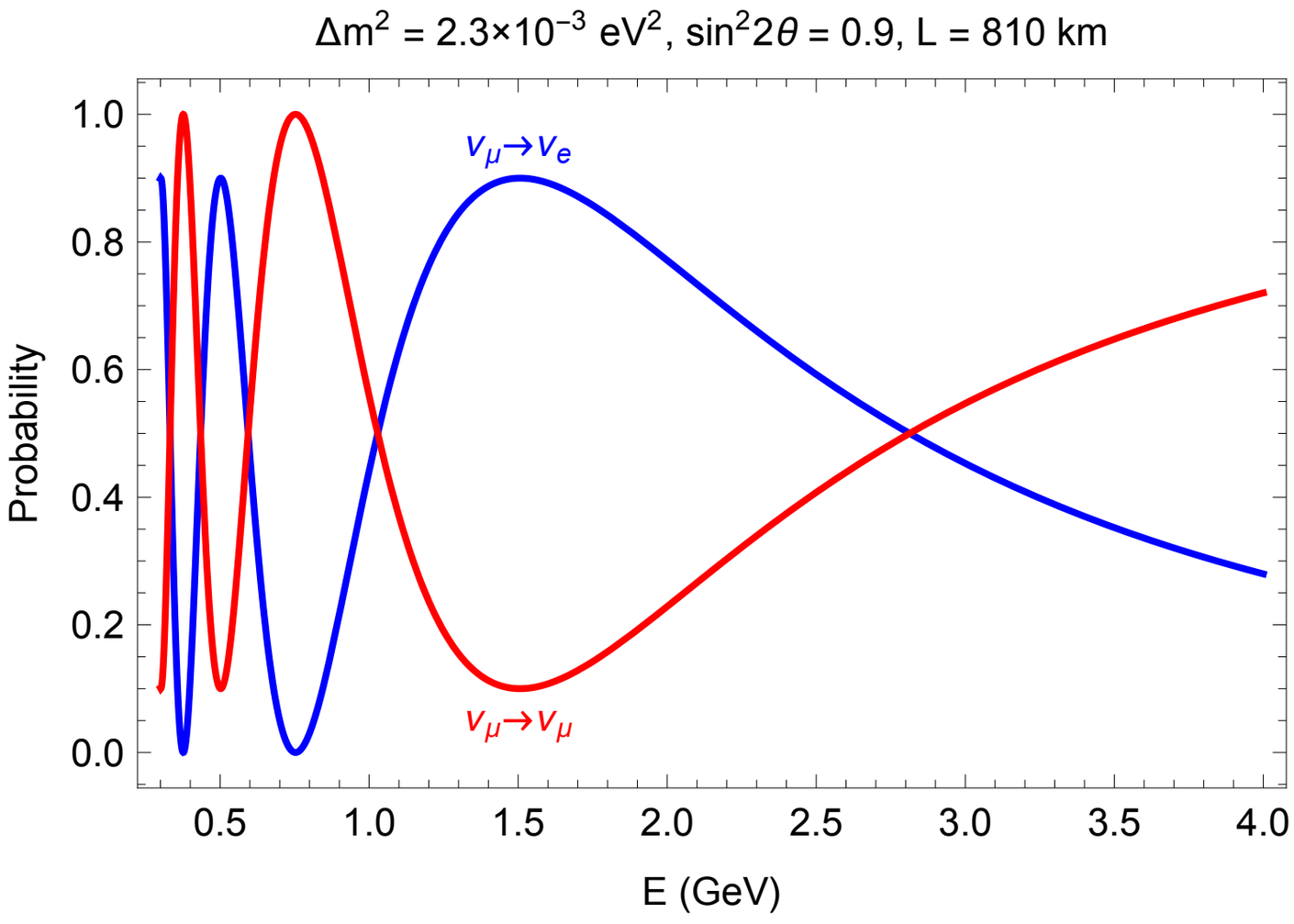
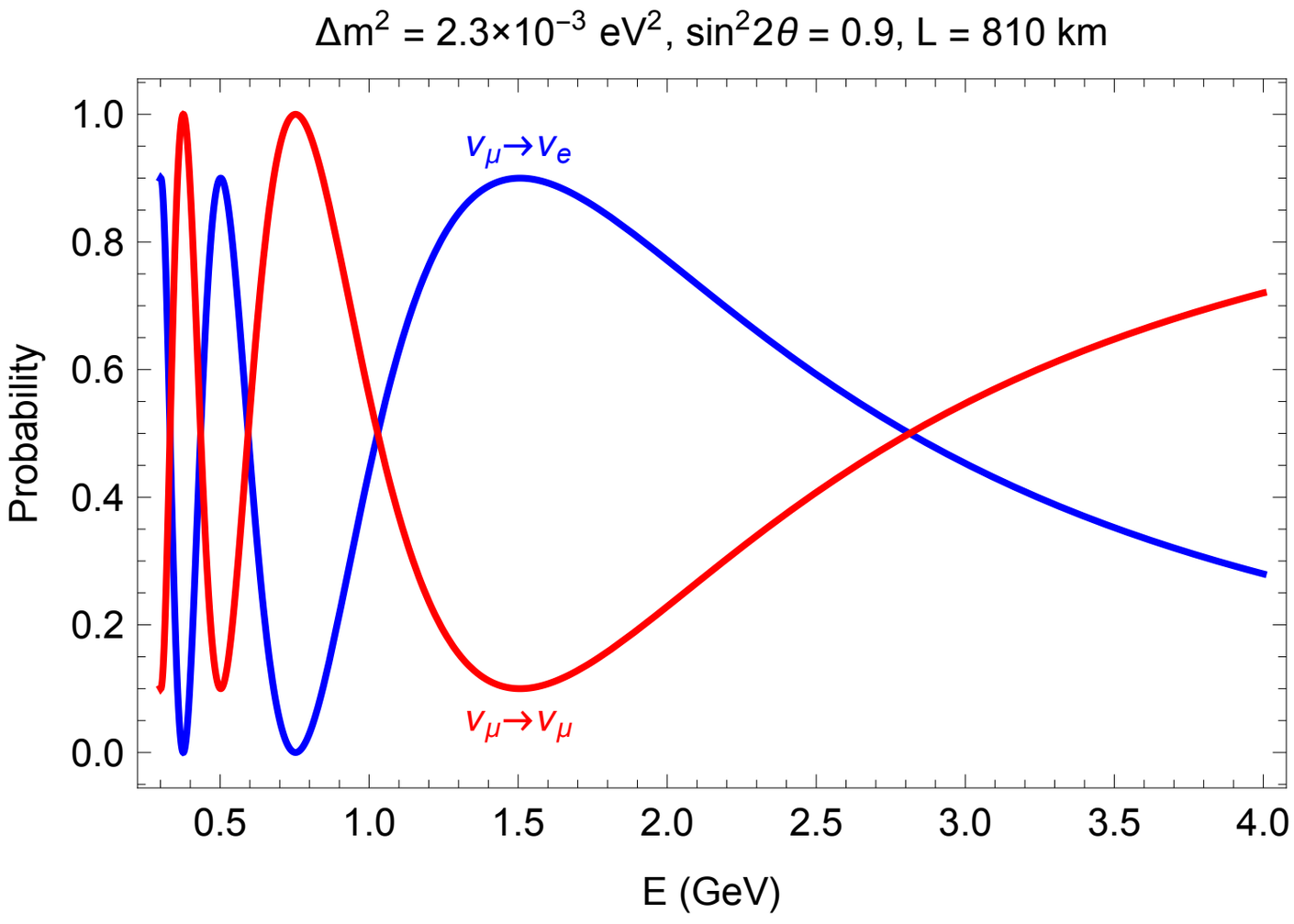


Neutrino Oscillations

$$P(\nu_\mu \to \nu_e; L) = |A_{\mu e}(L)|^2 = 4c_\theta^2 s_\theta^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



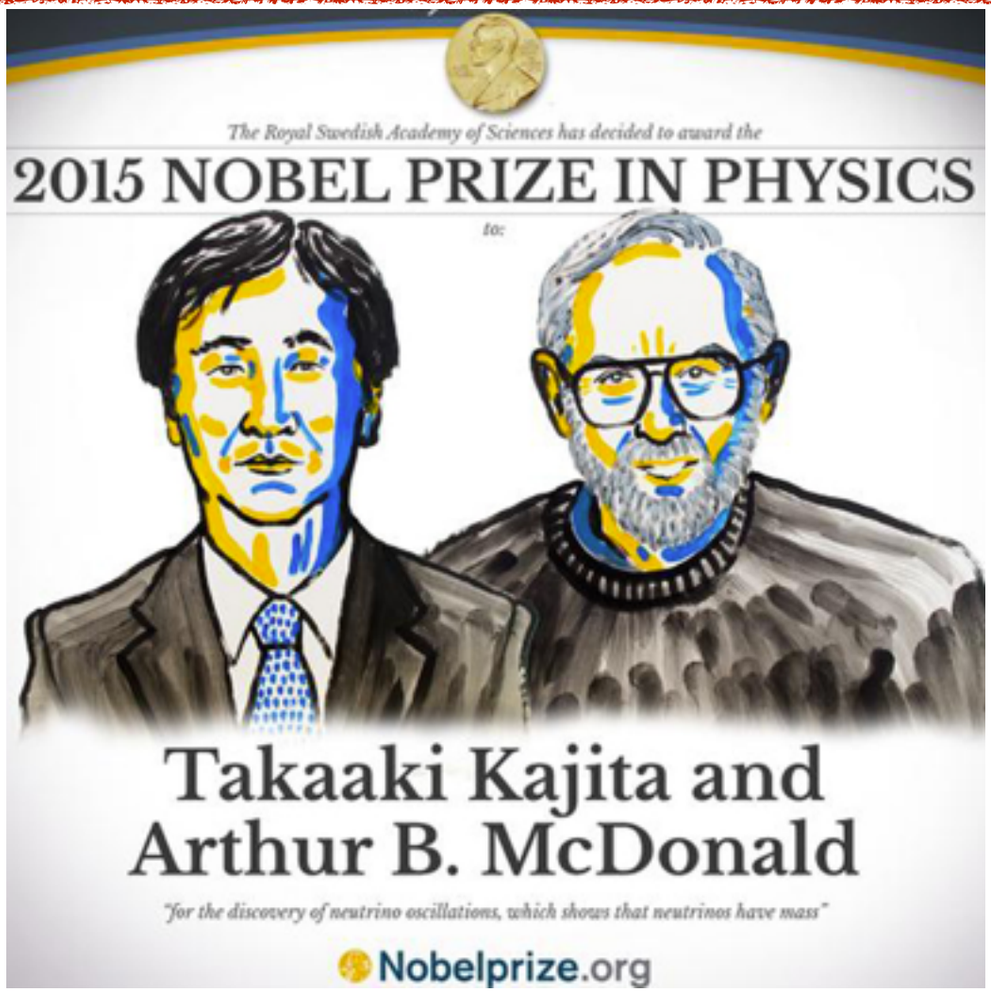
The probability of producing ν_μ and detect ν_e really *oscillates*!

Neutrino Oscillations

$$P(\nu_\mu \to \nu_e; L) = |A_{\mu e}(L)|^2 = 4c_\theta^2 s_\theta^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Neutrino oscillations necessarily imply neutrino masses, that is,

physics beyond the Standard Model



2015 Nobel prize for the discovery of neutrino oscillations, which shows that neutrinos have mass

Neutrino Oscillations

With three families there are 3 mixing angles,
2 mass splittings and one complex phase!

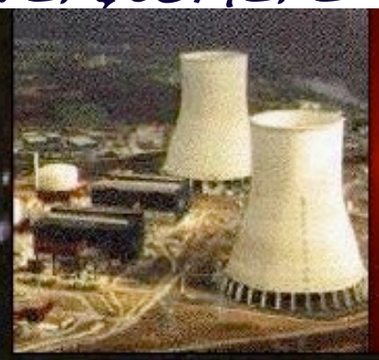
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

What do we know about
neutrinos and their oscillations?

Neutrinos

Neutrinos are everywhere ...

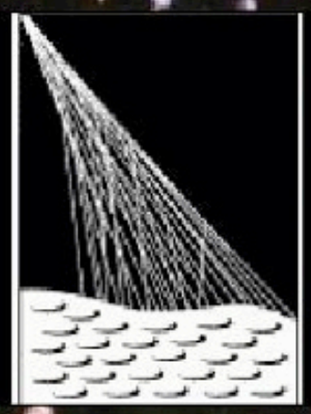


Nuclear Reactors

SUN

Accelerators

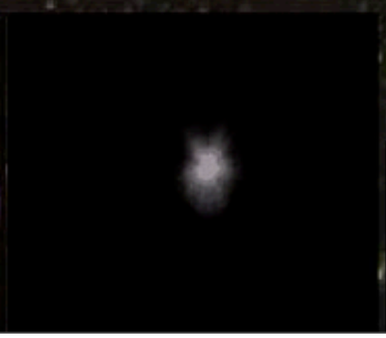
Supernova
(Stellar Collapse)



Atmospheric
(Cosmic Rays)

Astrophysical
Accelerators

Earth's
Crust/Mantle



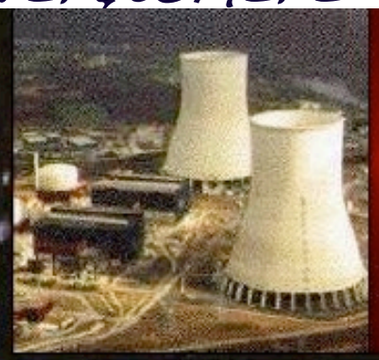
Big Bang
(330 ν /cm^3)

From R. Zukanovich Funchal Invisibles School 2014

Neutrinos

Neutrinos are everywhere ...

$\overline{\nu}_e$ **Nuclear Reactors**

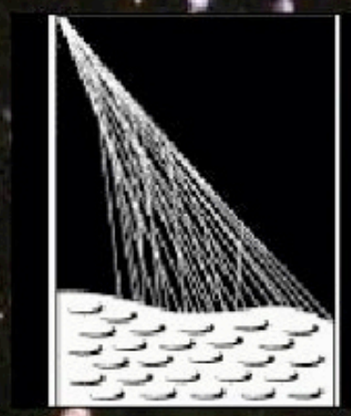


SUN ν_e

$\nu_{\mu,all}$ **Accelerators**

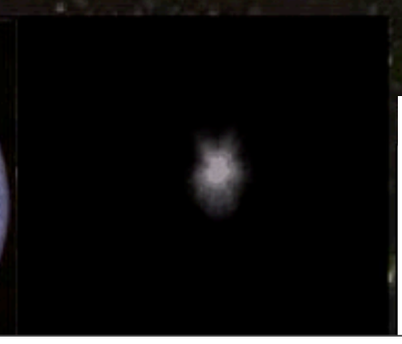
Supernova (Stellar Collapse) ν_{all}

ν_{all} **Atmospheric (Cosmic Rays)**



Astrophysical Accelerators ν_{all}

$\overline{\nu}_e$ **Earth's Crust/Mantle**



Big Bang (330 ν /cm^3) ν_{all}

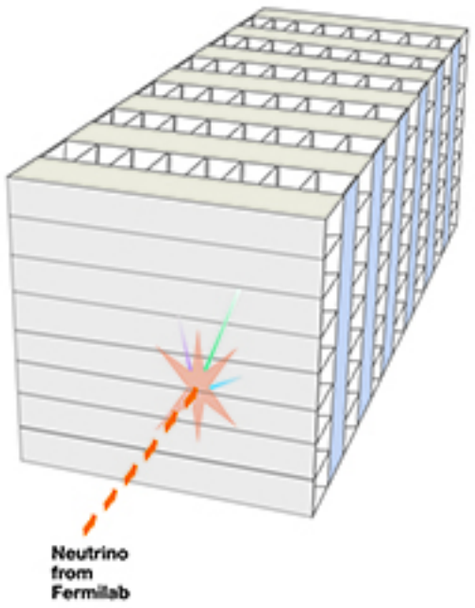
From R. Zukanovich Funchal Invisibles School 2014

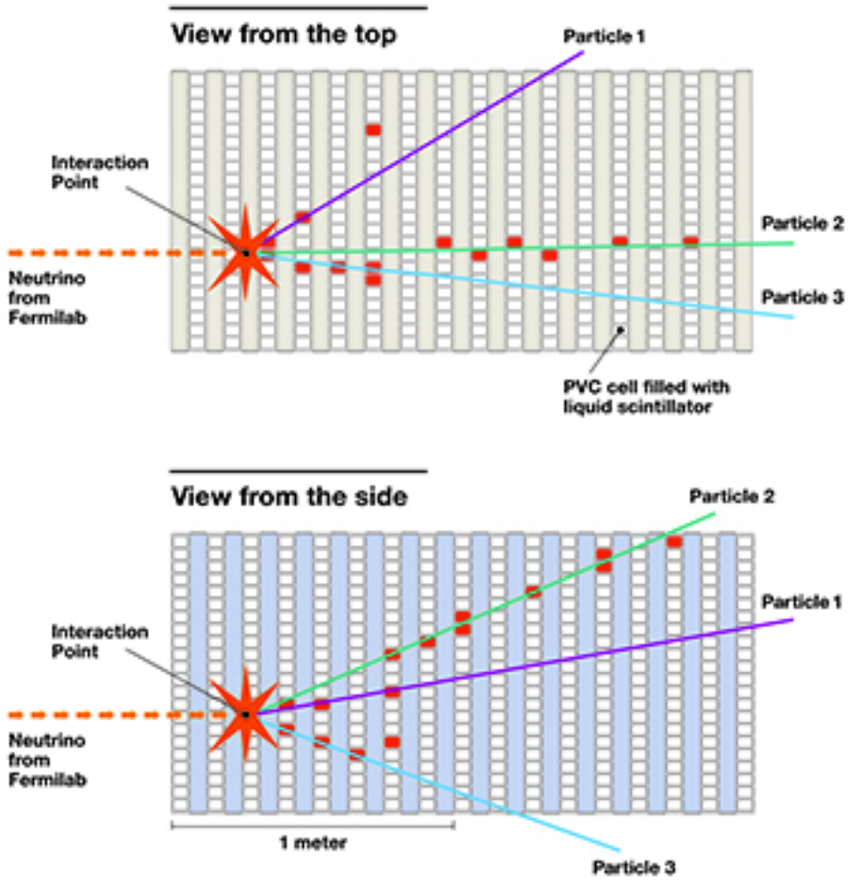
Neutrino Oscillations

The following is **not** in chronological order

NOvA Experiment

3D schematic of
NOvA particle detector





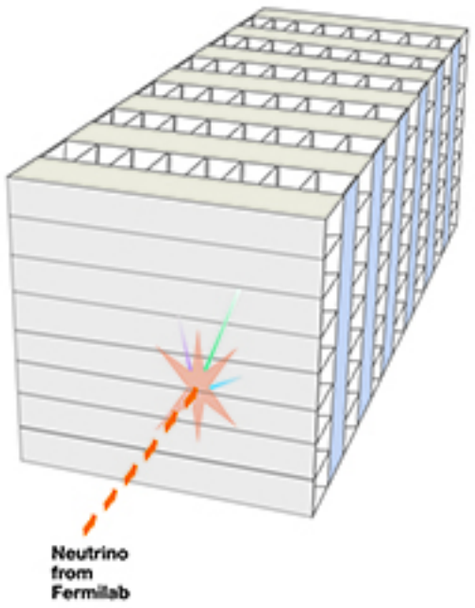
Fermilab

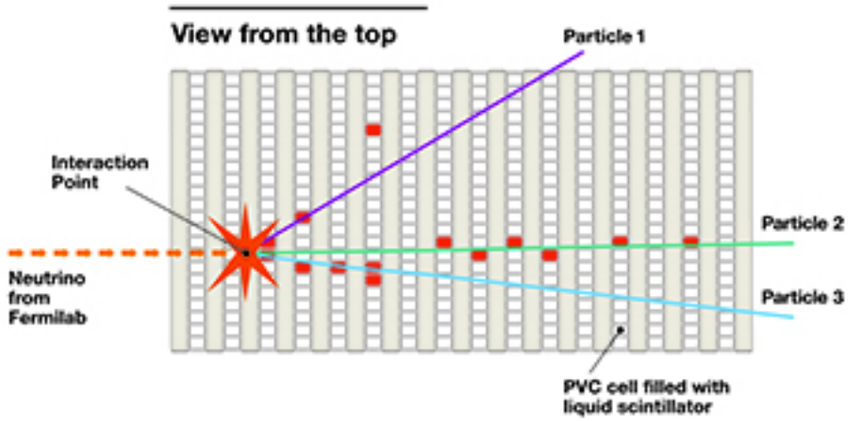
L = 810 km

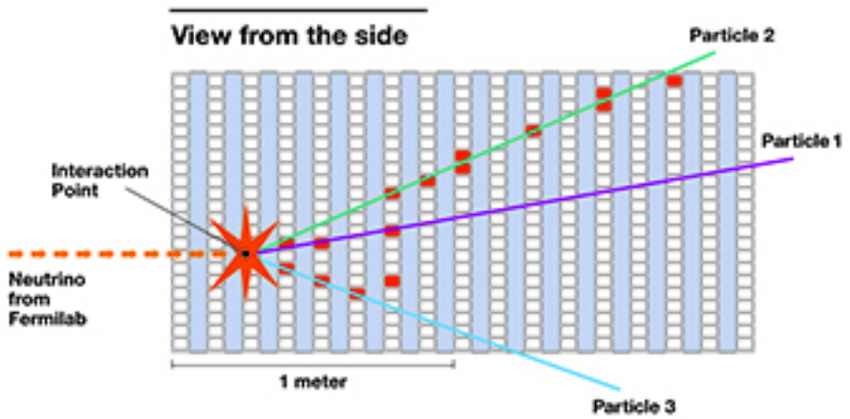
(from FNAL to Minnesota)

NOvA Experiment

3D schematic of
NOvA particle detector





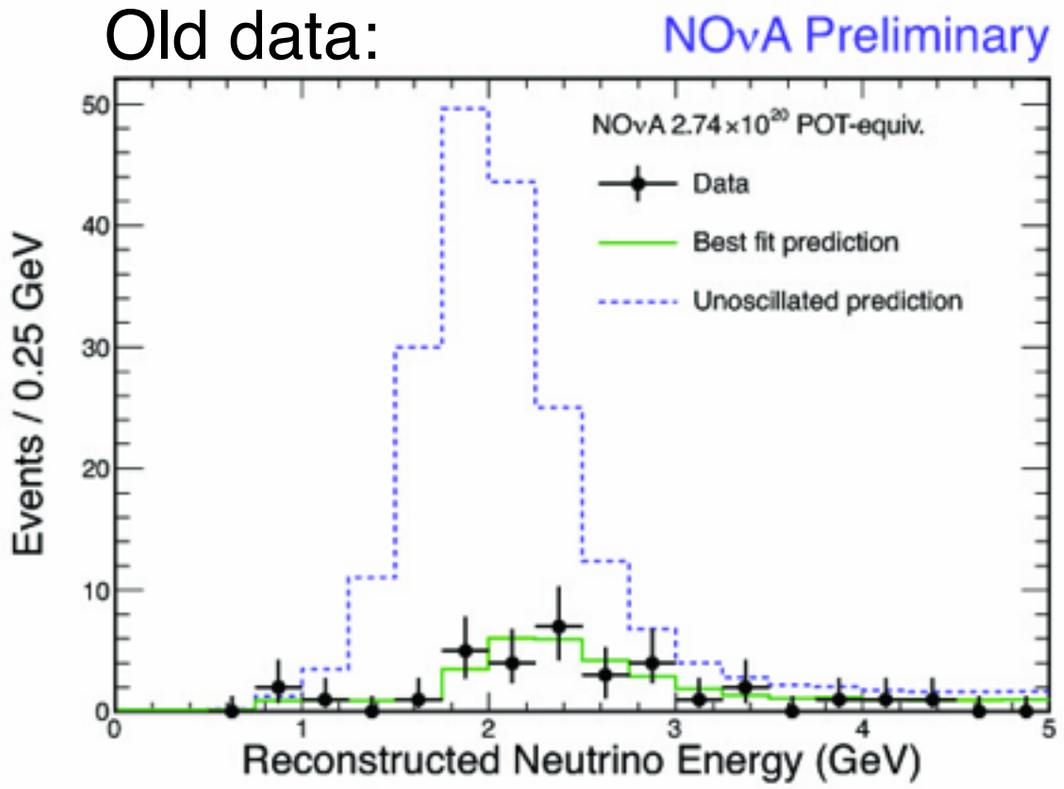


Fermilab

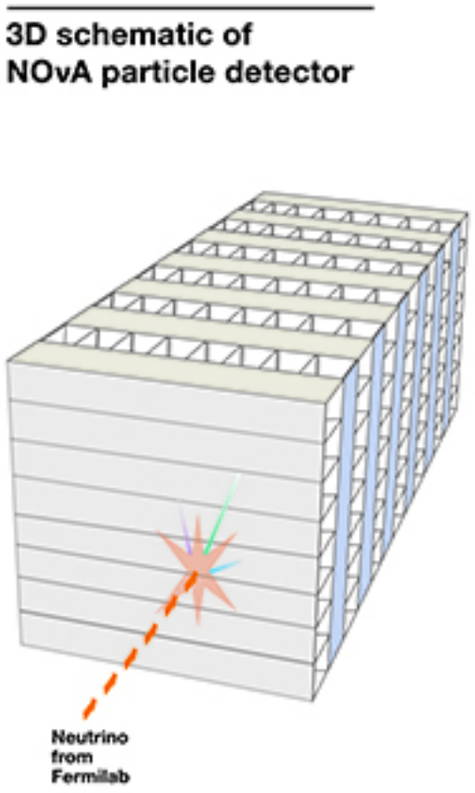
L = 810 km
(from FNAL to Minnesota)

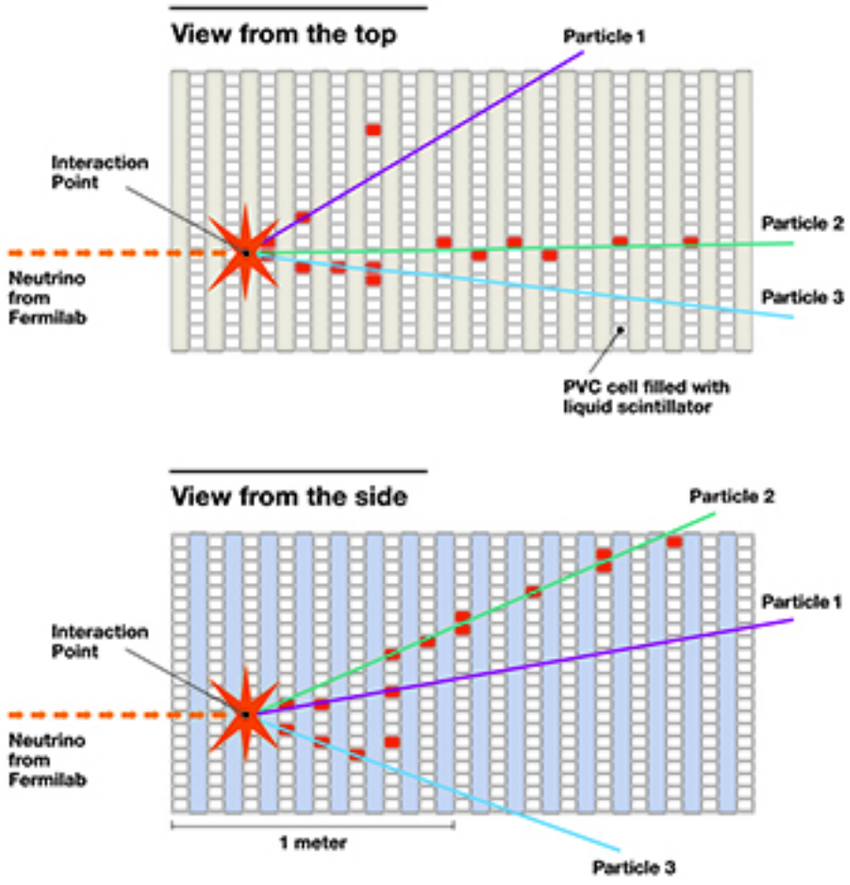
ν_μ to ν_μ

Old data:



NOvA Experiment





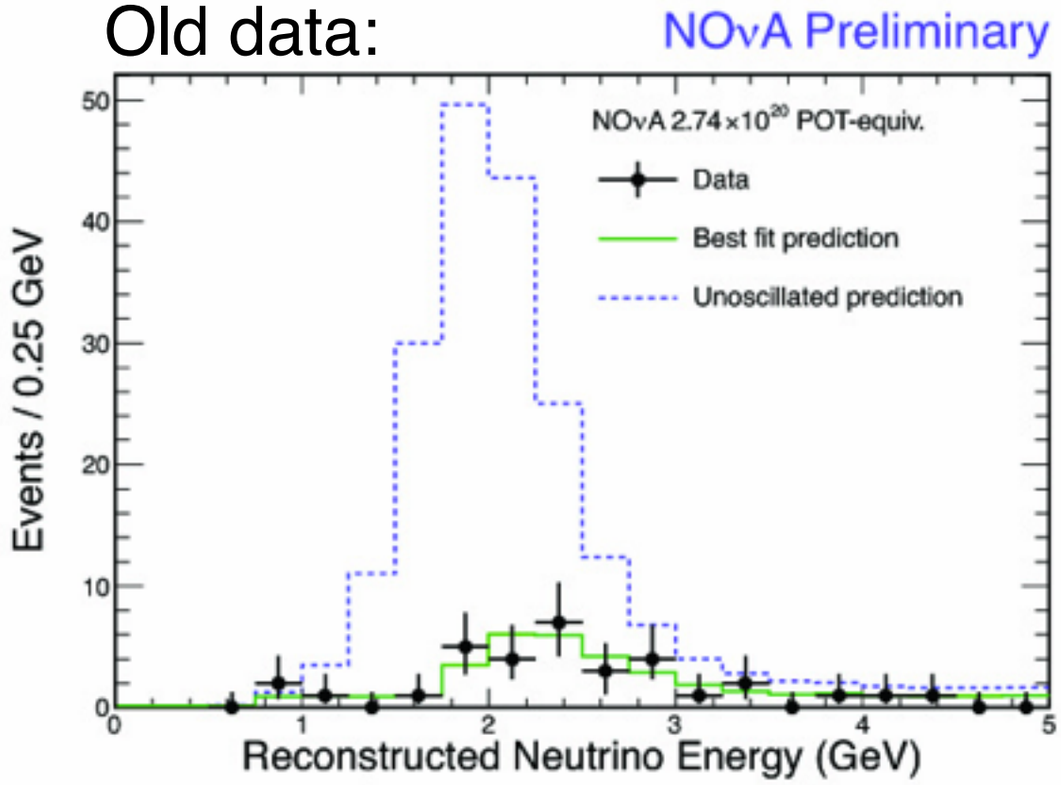
Fermilab

L = 810 km

(from FNAL to Minnesota)

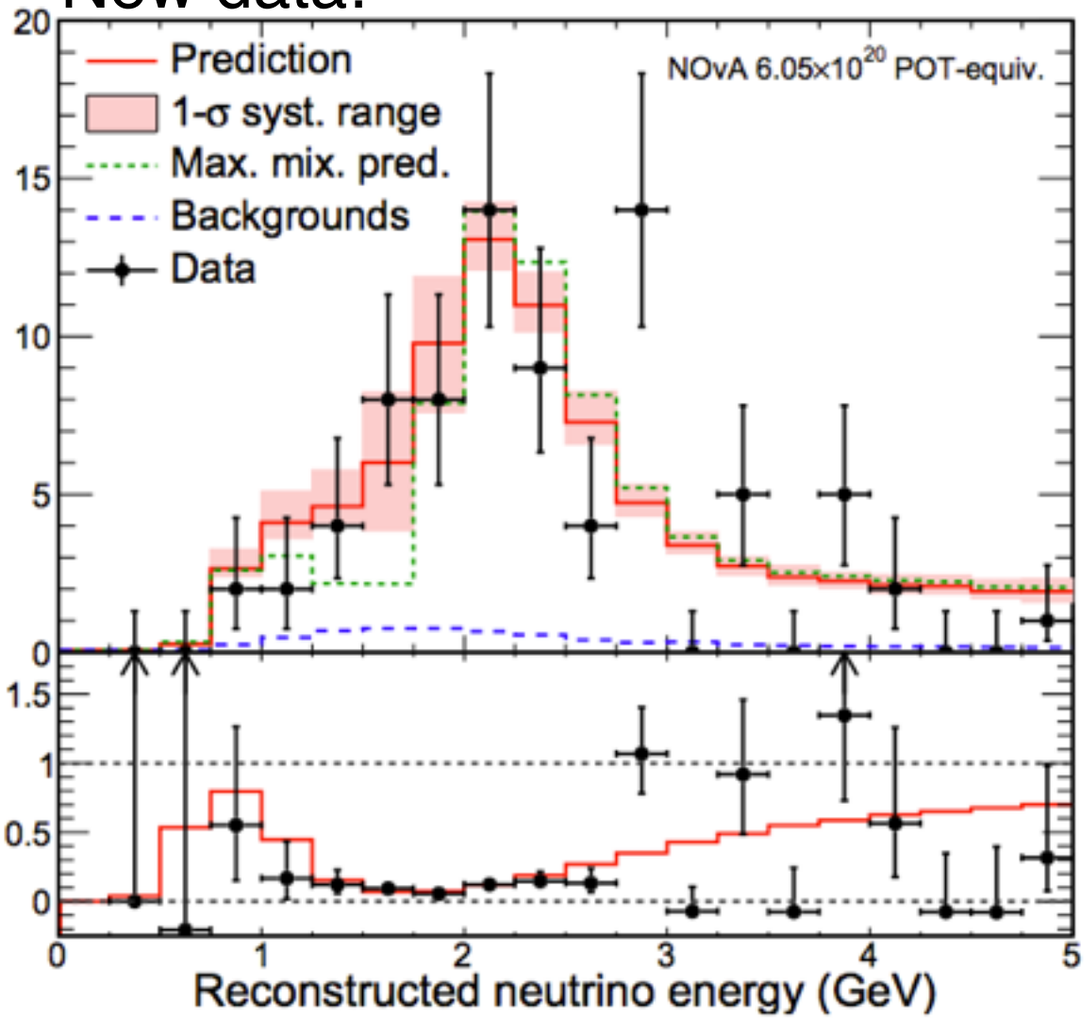
ν_μ to ν_μ

Old data:

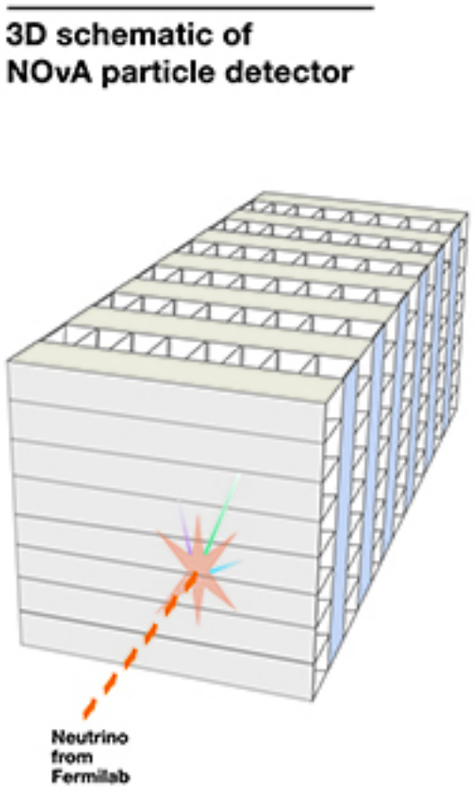


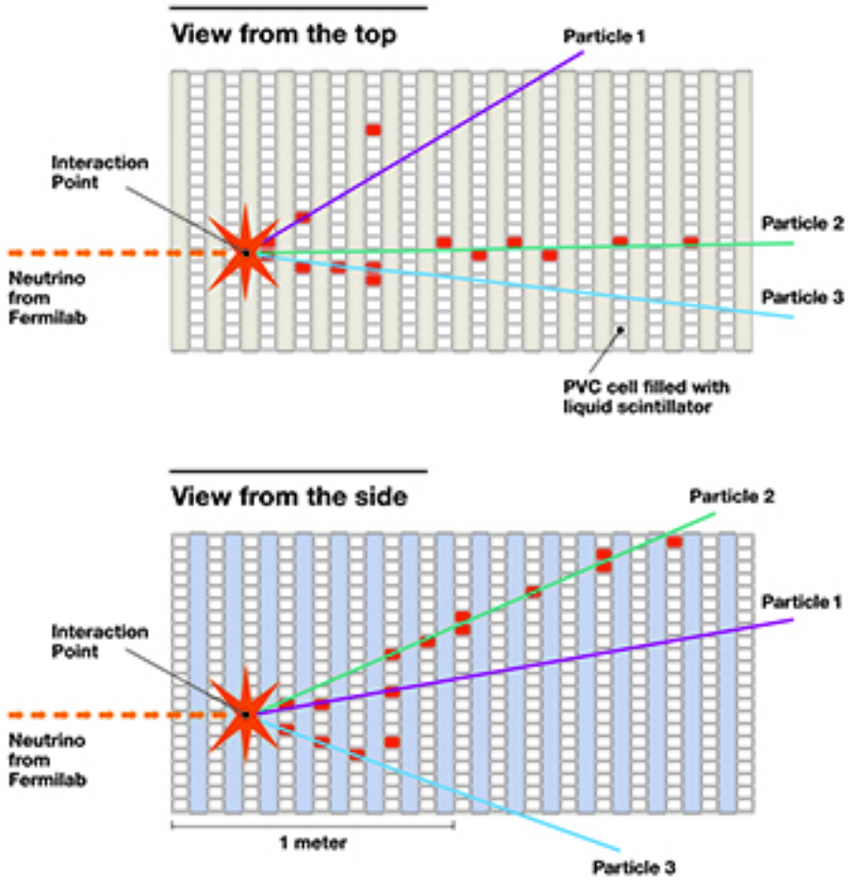
ν_μ to ν_μ

New data:



NOvA Experiment

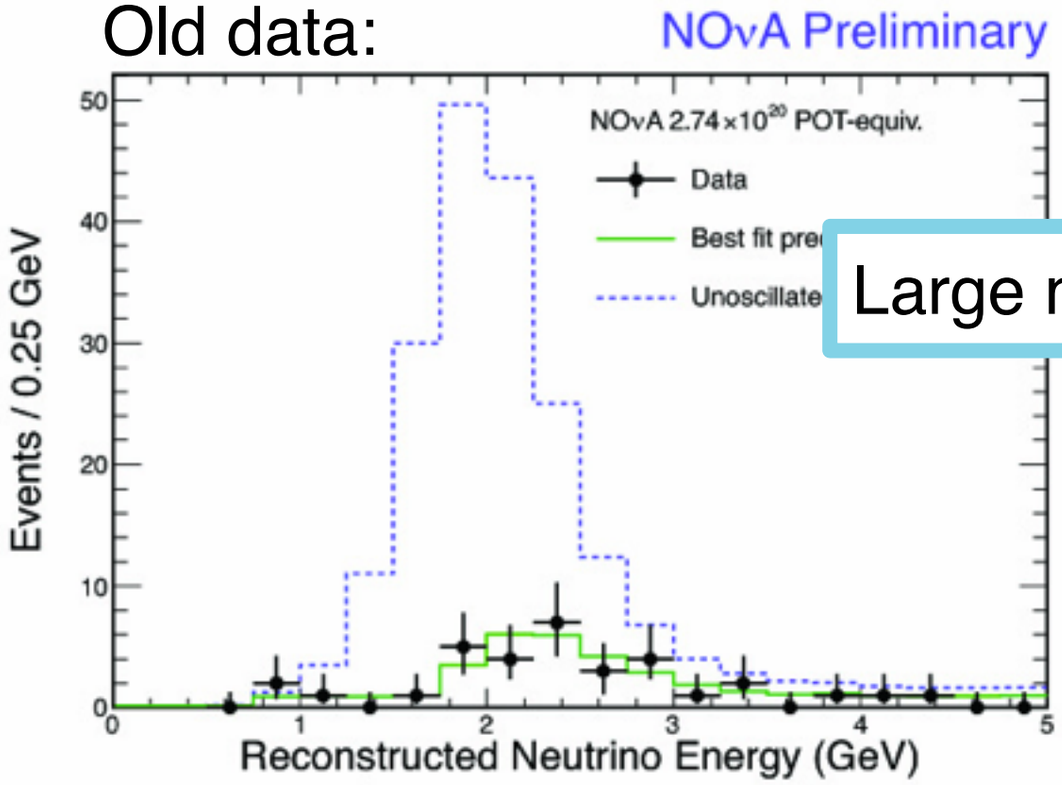




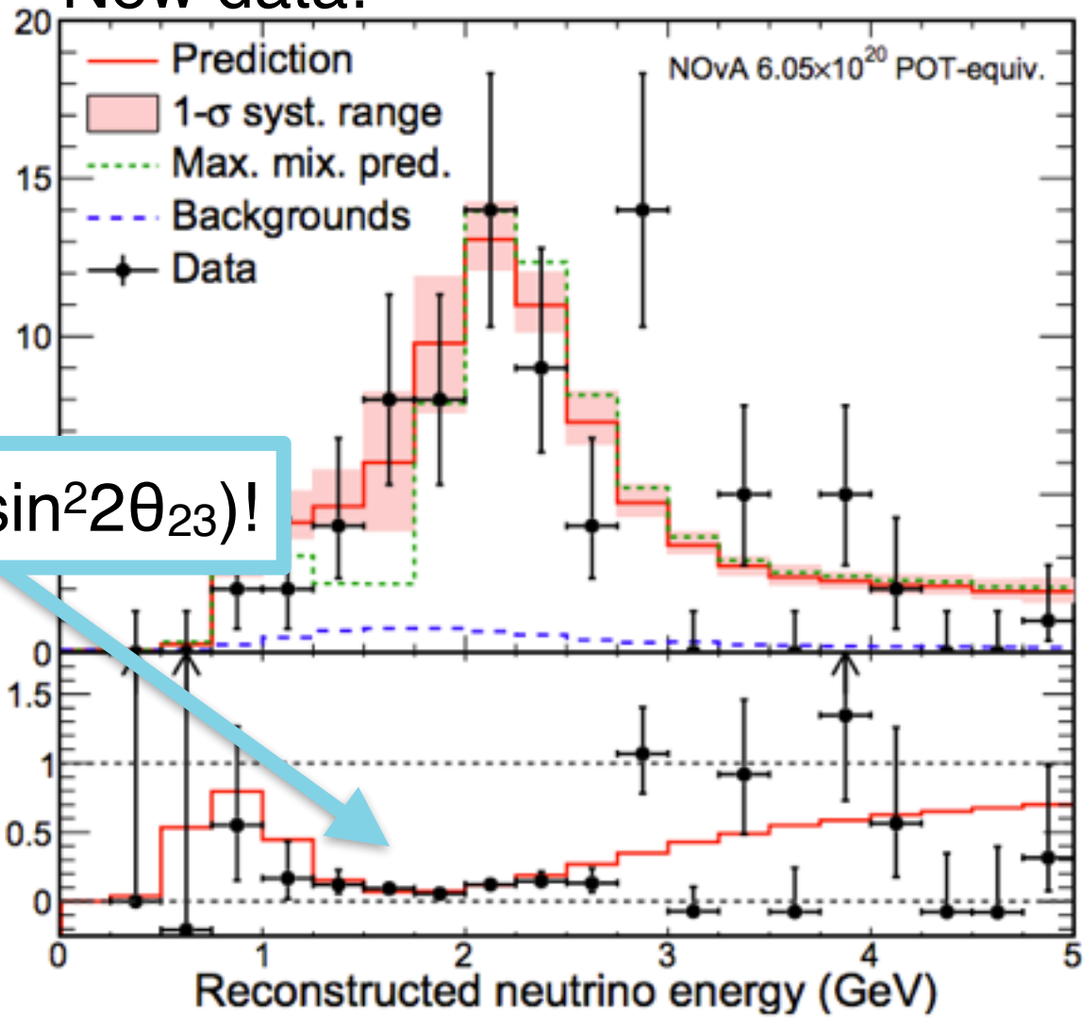
Fermilab

L = 810 km
(from FNAL to Minnesota)

ν_μ to ν_μ
Old data:

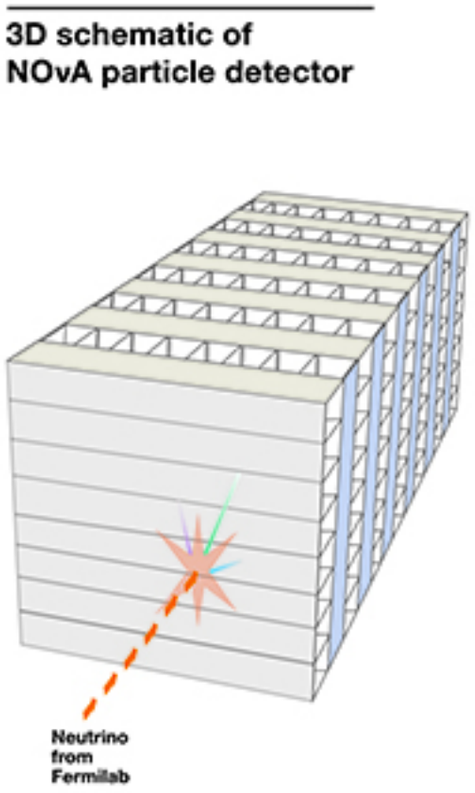


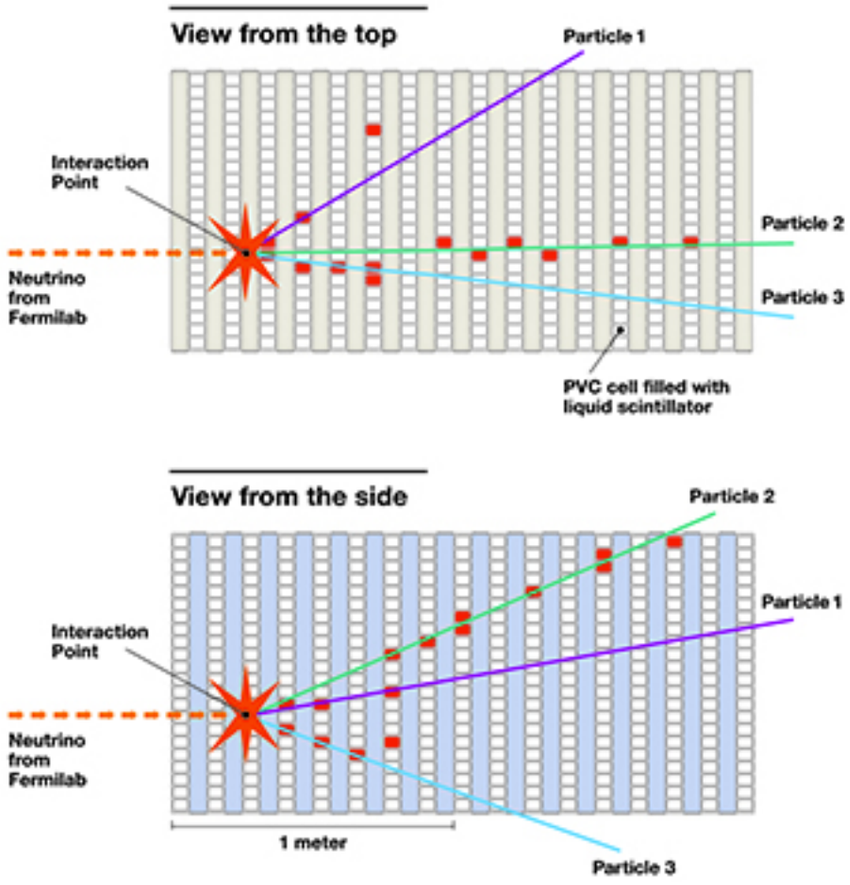
ν_μ to ν_μ
New data:



Large mixing ($\sin^2 2\theta_{23}$)!

NOvA Experiment





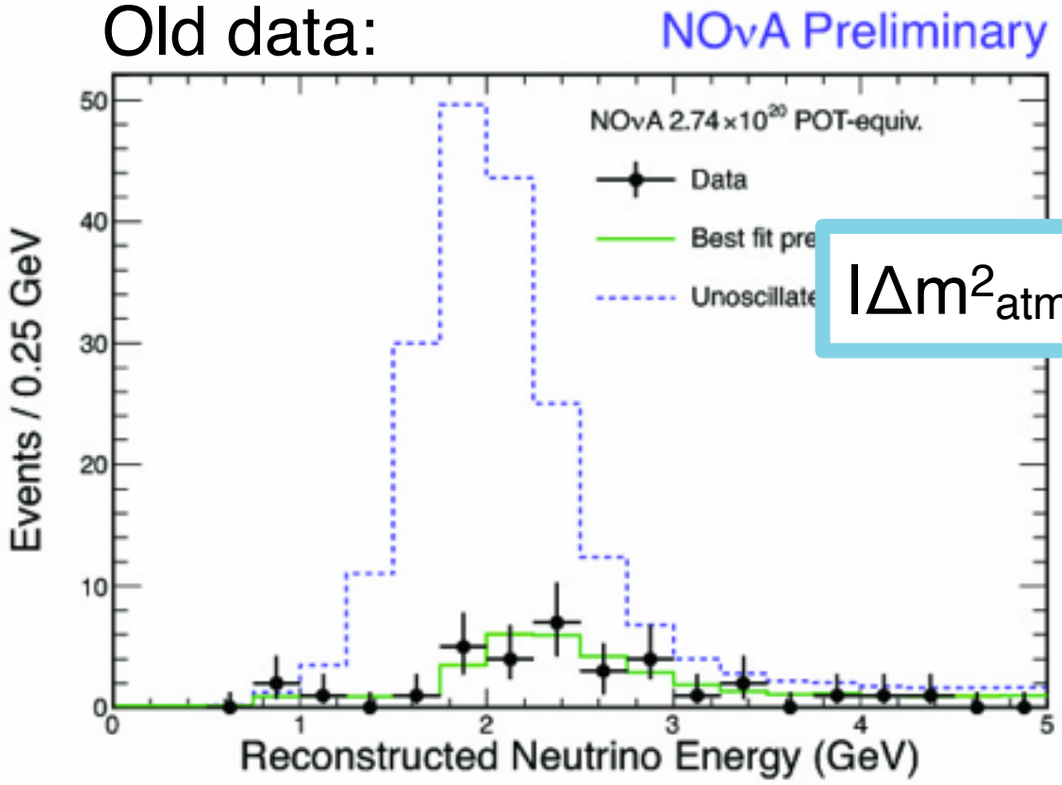
Fermilab

L = 810 km

(from FNAL to Minnesota)

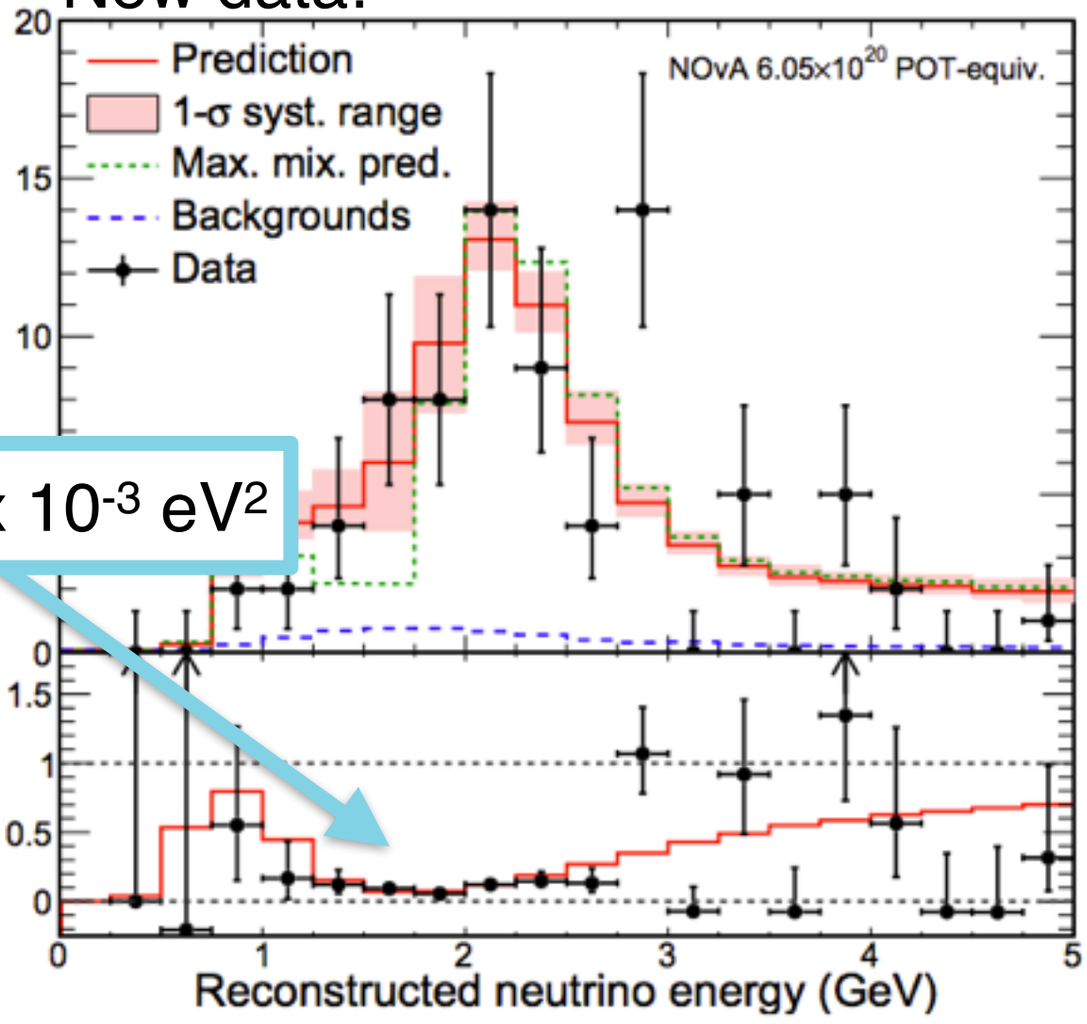
ν_μ to ν_μ

Old data:



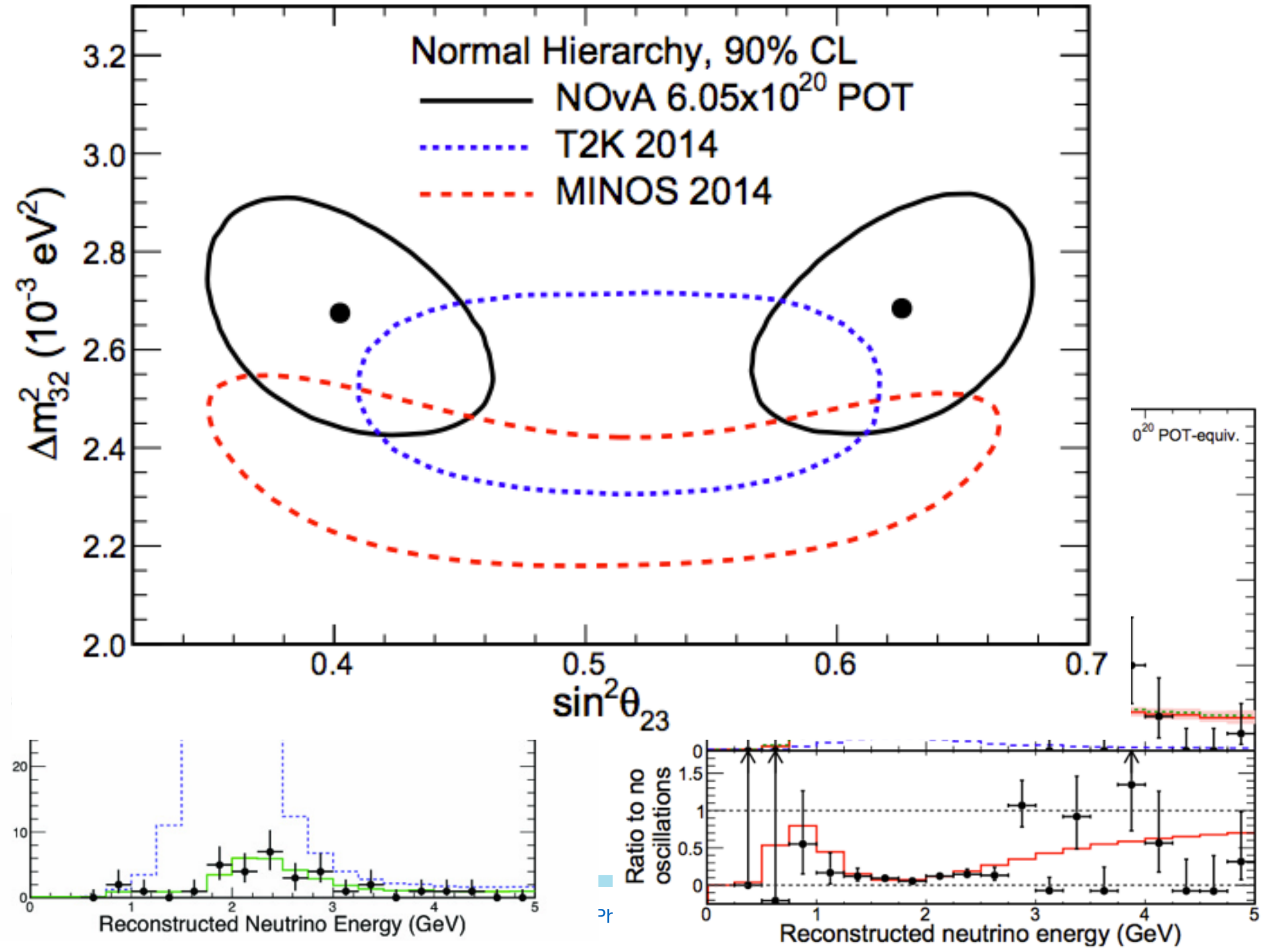
ν_μ to ν_μ

New data:



$|\Delta m^2_{atm}| \sim 2.7 \times 10^{-3}\ eV^2$

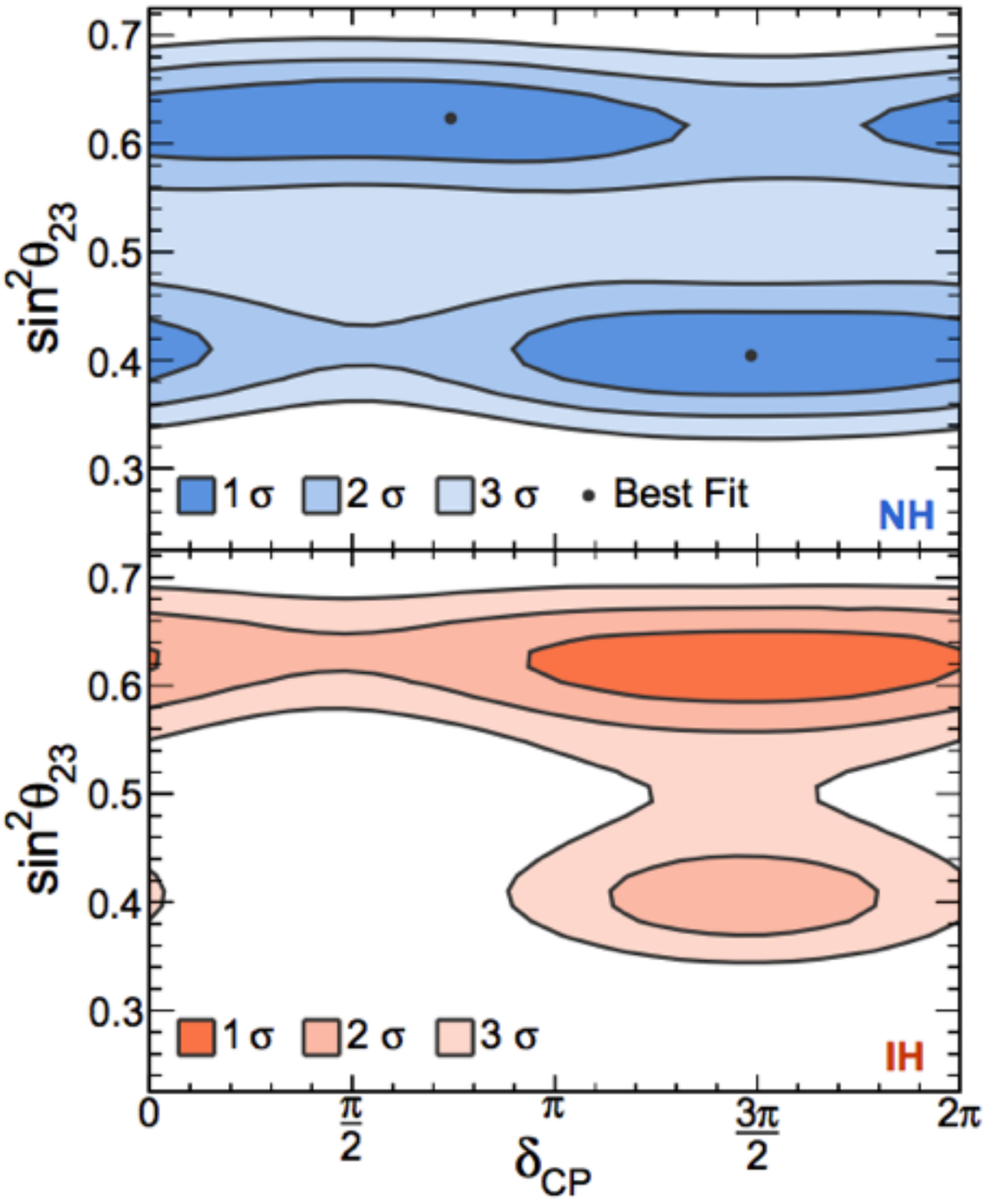
NOvA Experiment



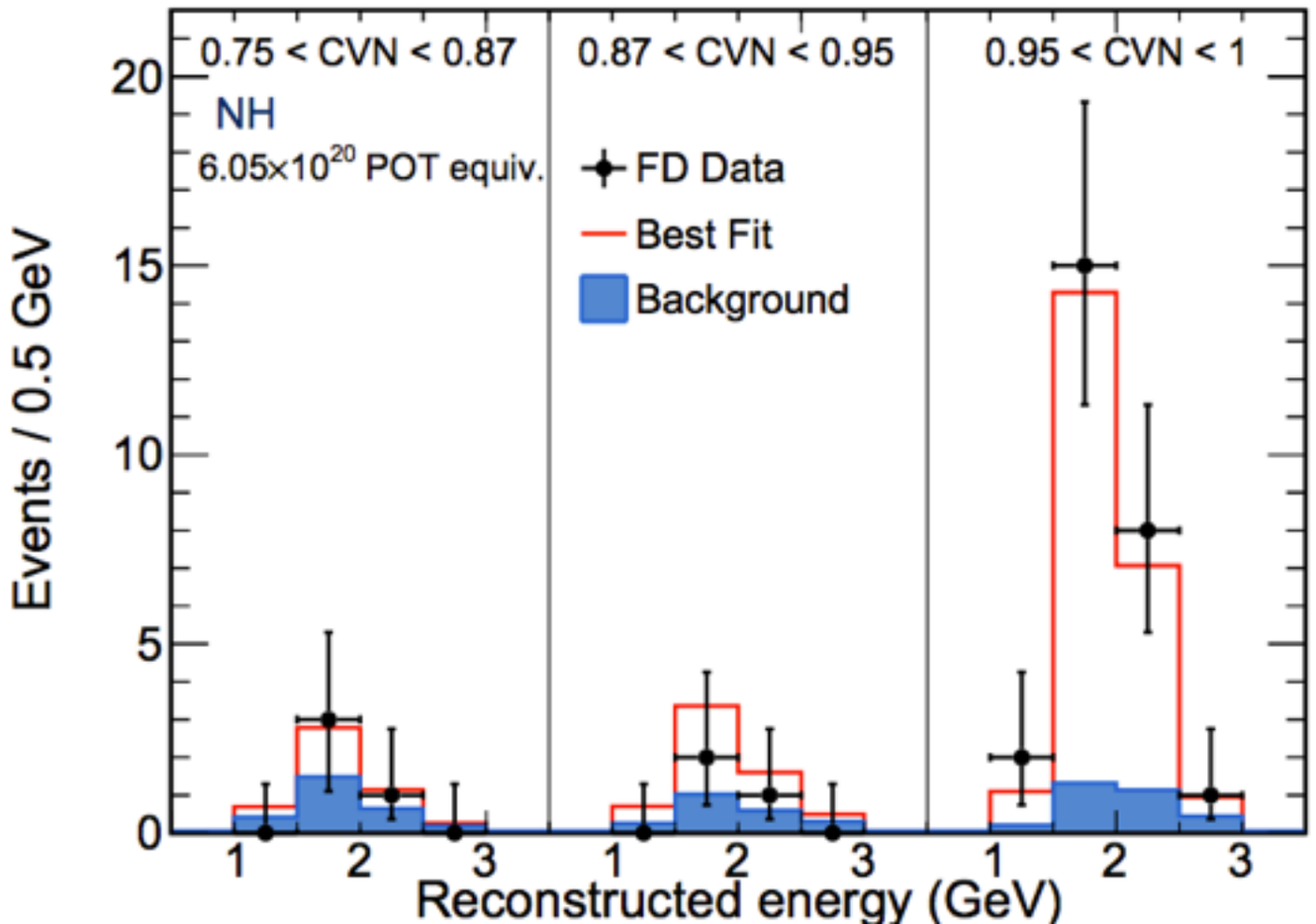
NOvA Experiment

Fermilab

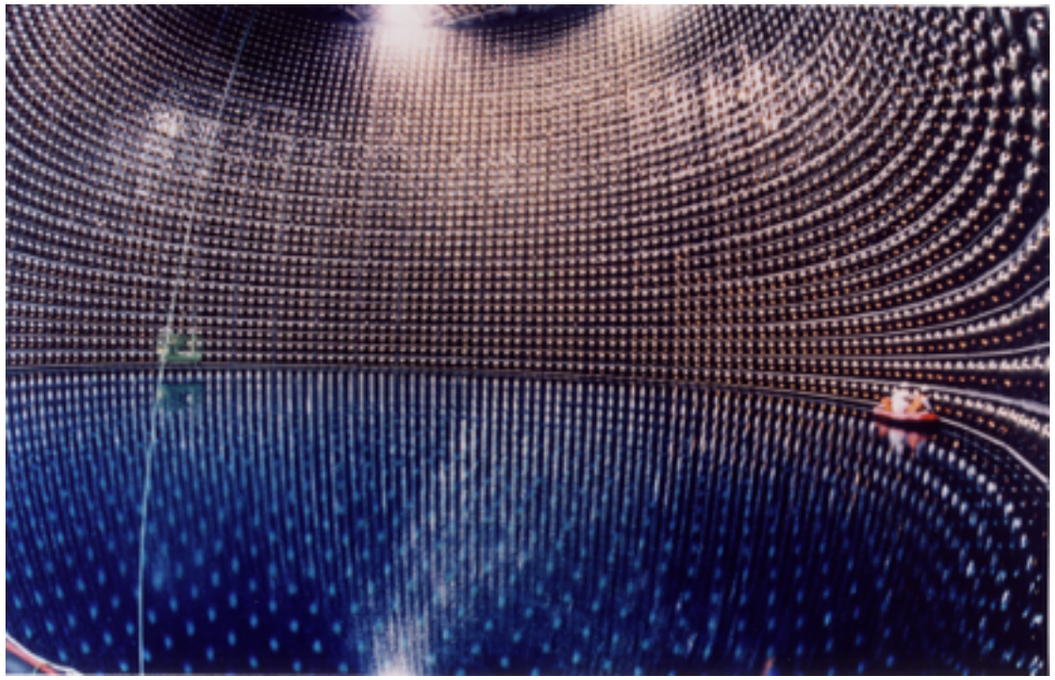
Sensitive to
smaller mixing angle (θ_{13})
and to CP violating phase
δ!

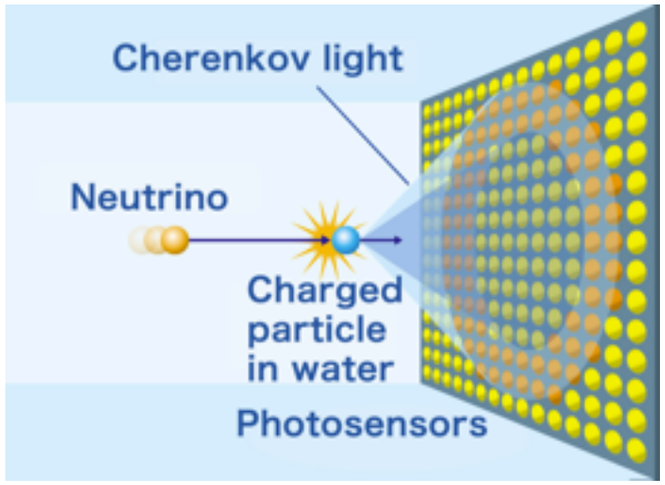


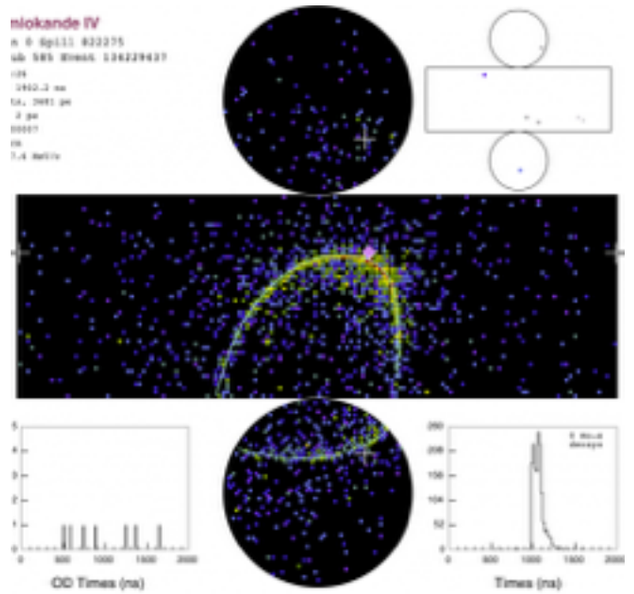
ν_μ to ν_e:



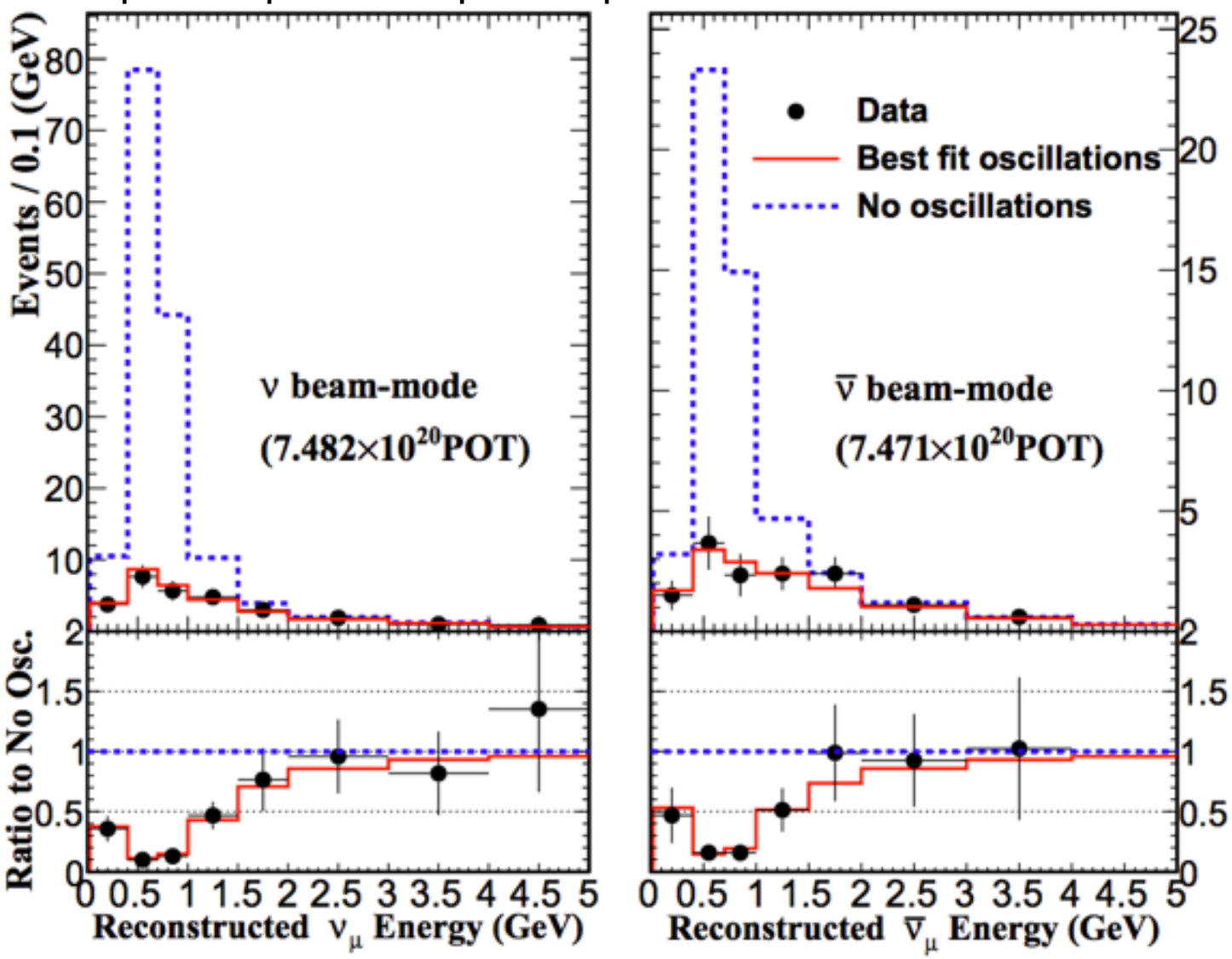
T2K Experiment



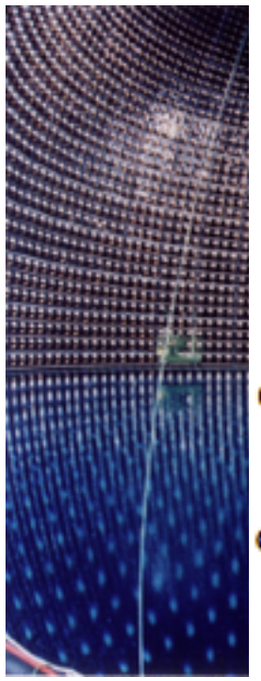


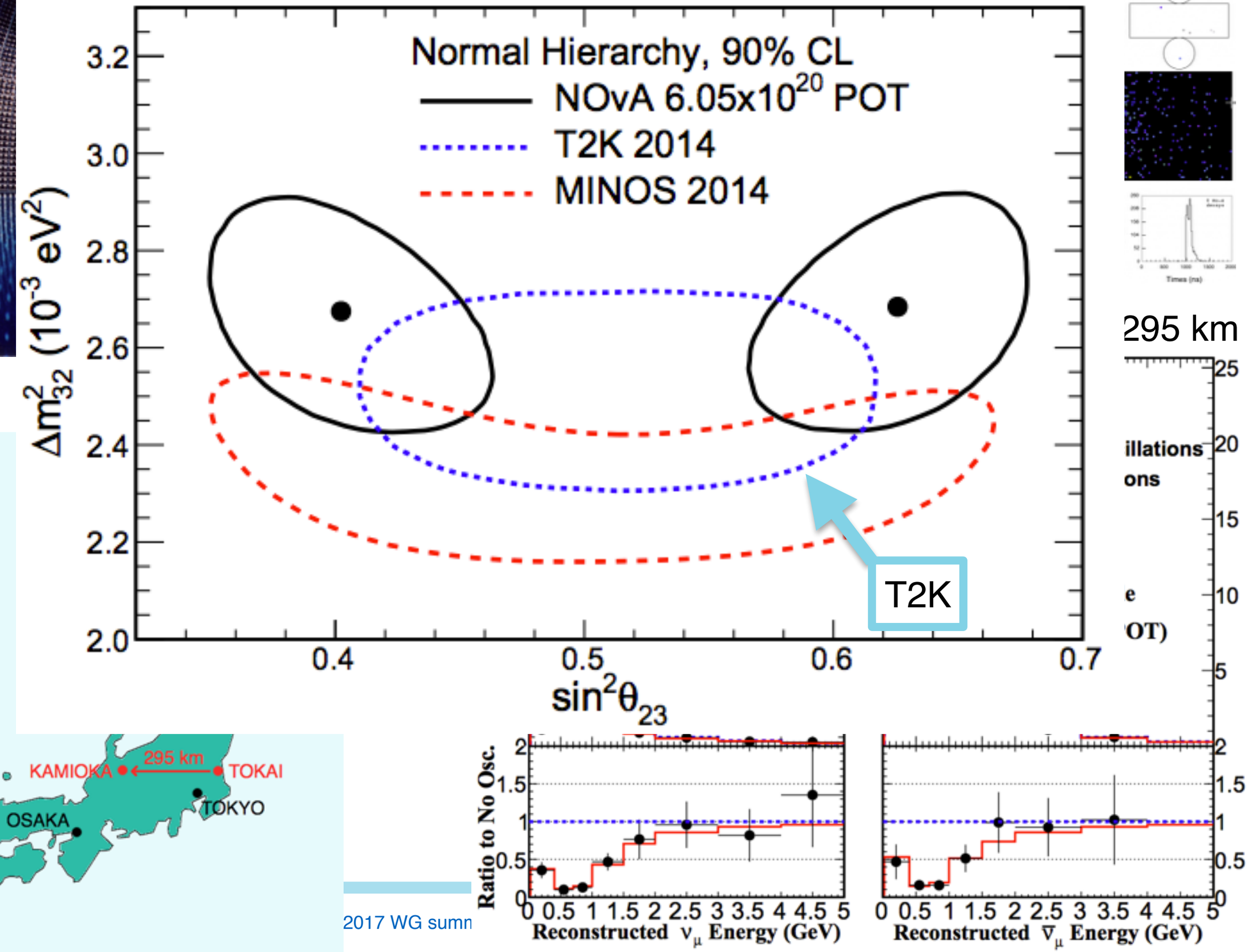


ν_μ to ν_μ and $\bar{\nu}_\mu$ to $\bar{\nu}_\mu$: L = 295 km



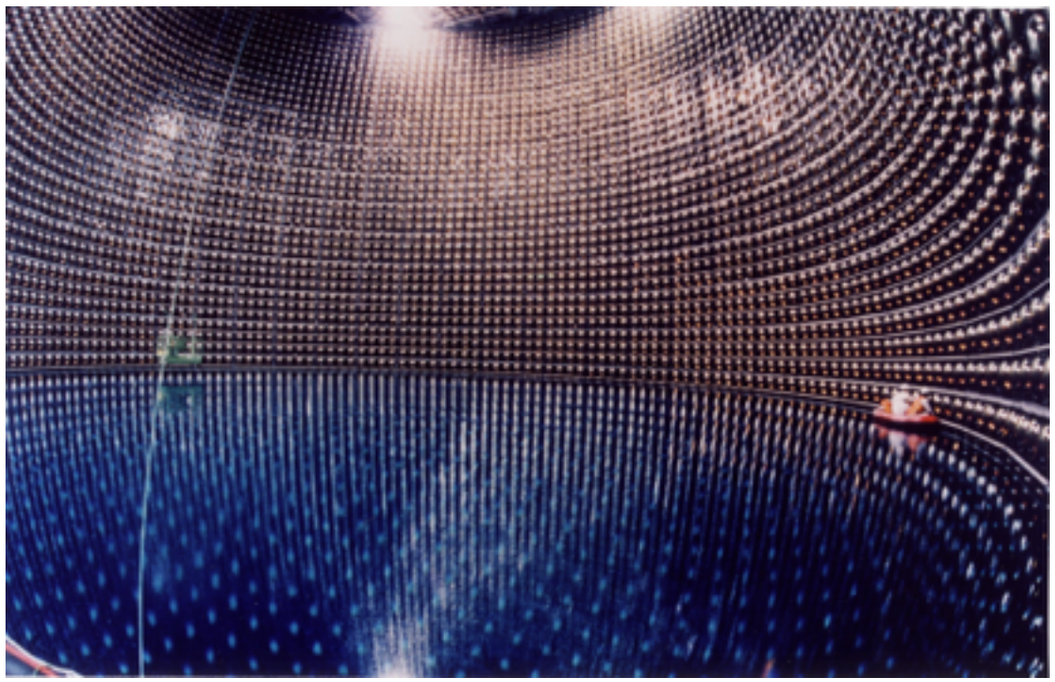
T2K Experiment

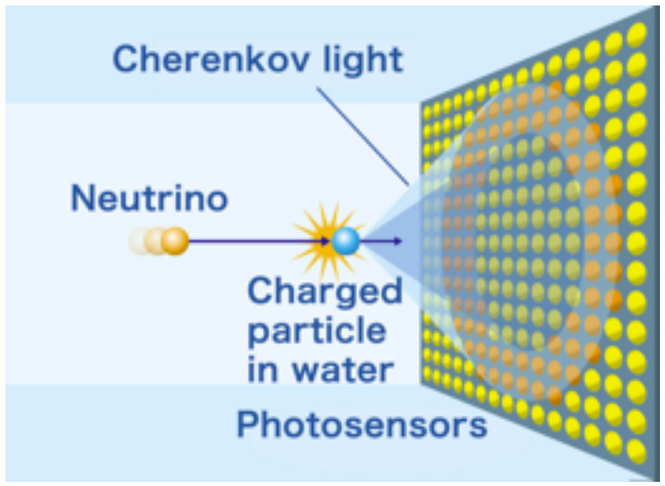


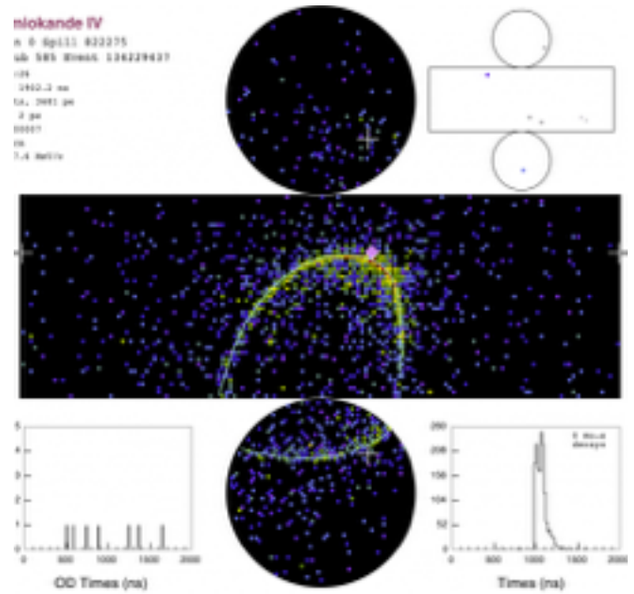


295 km

T2K Experiment

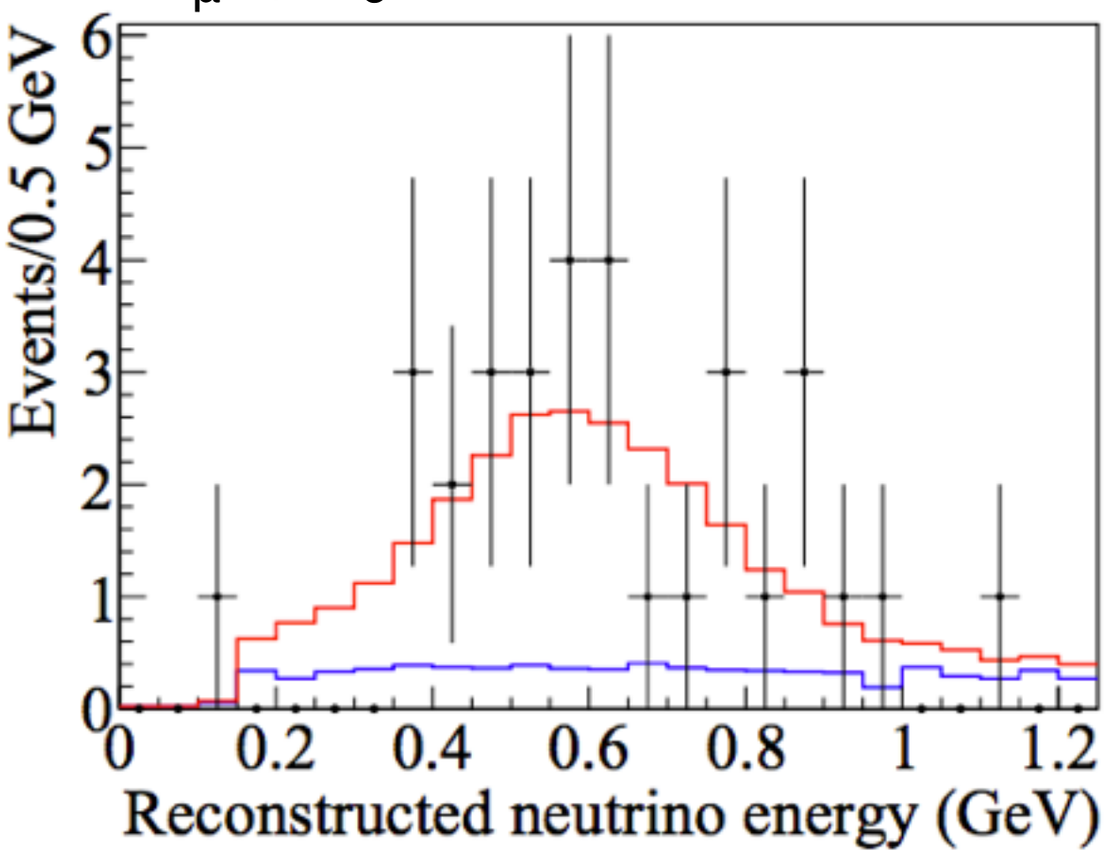




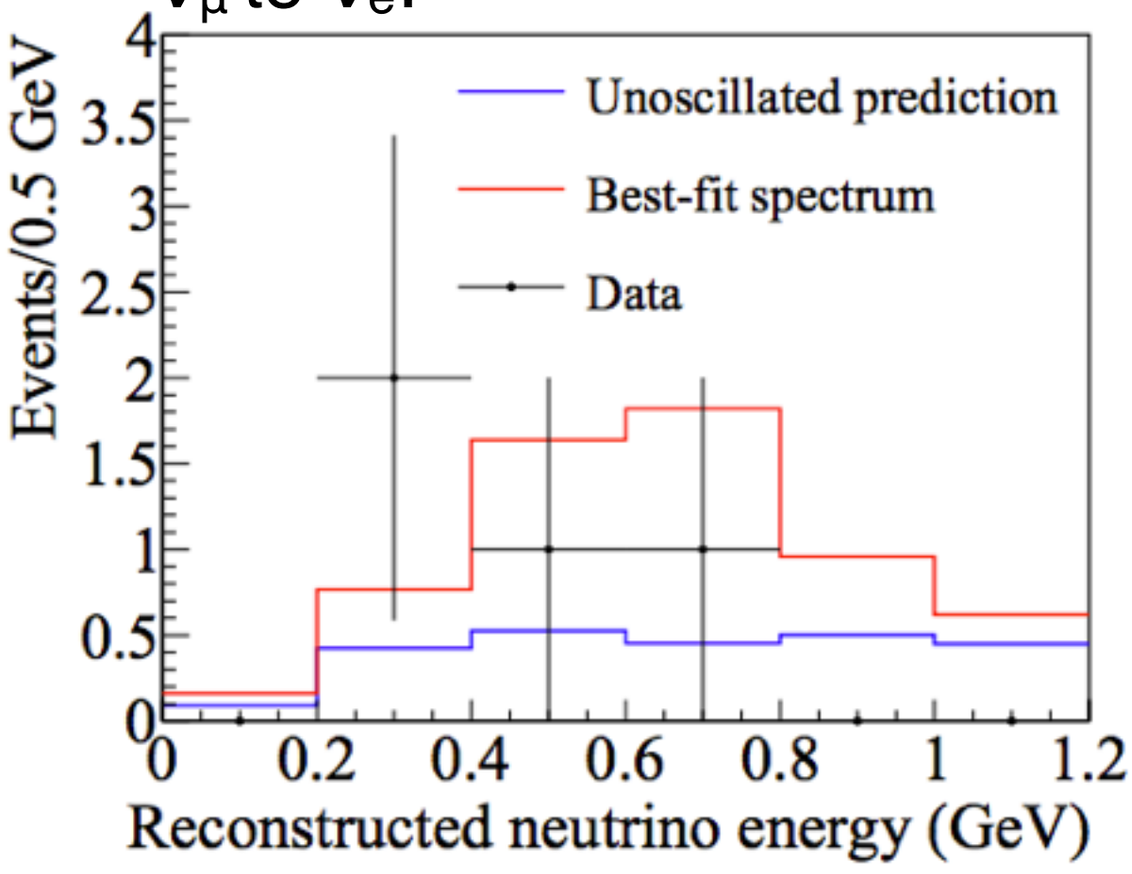


L = 295 km

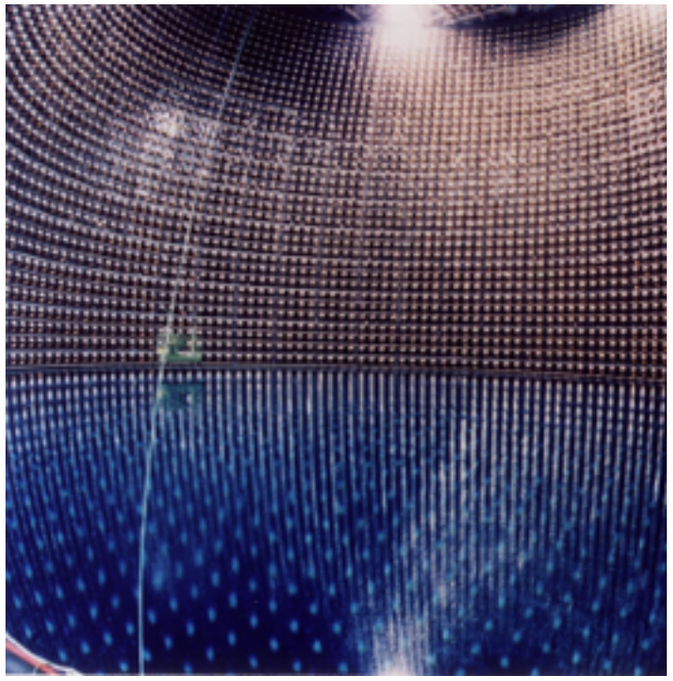
ν_μ to ν_e:

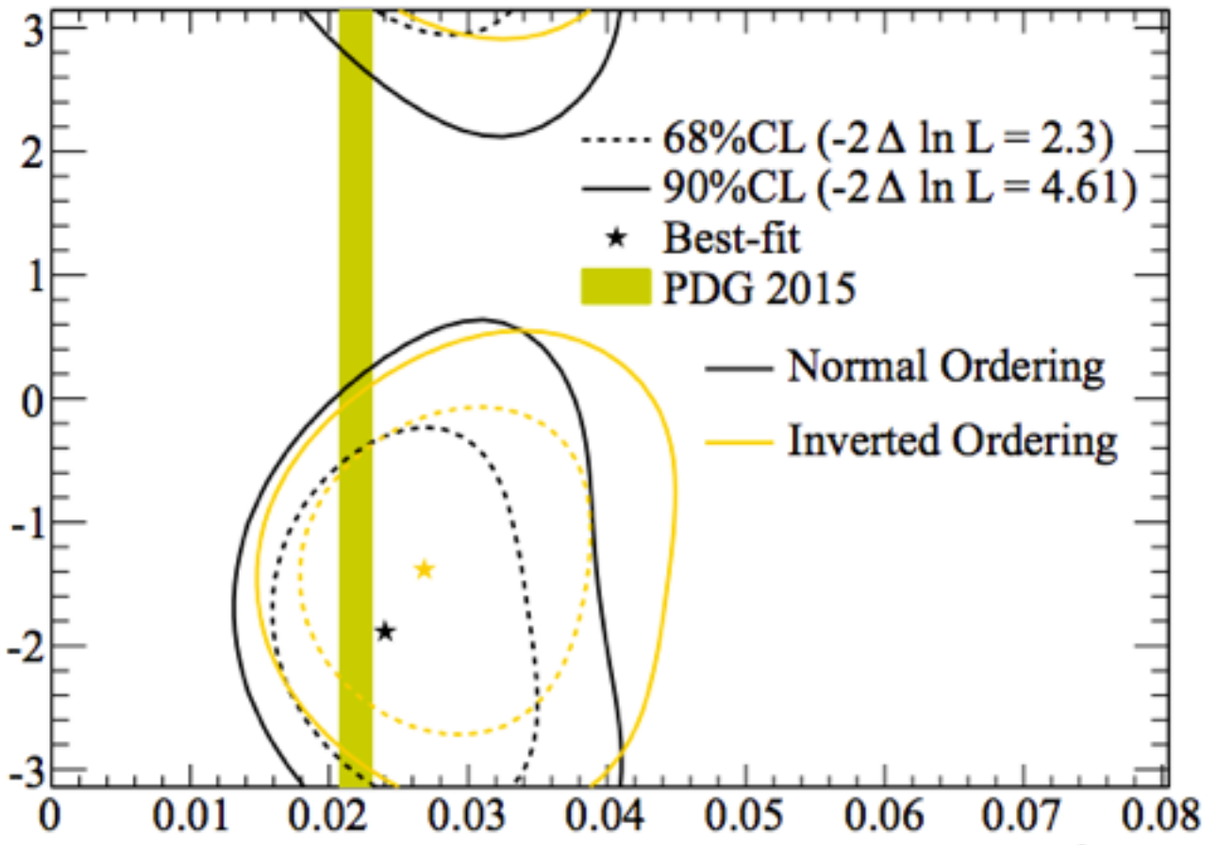


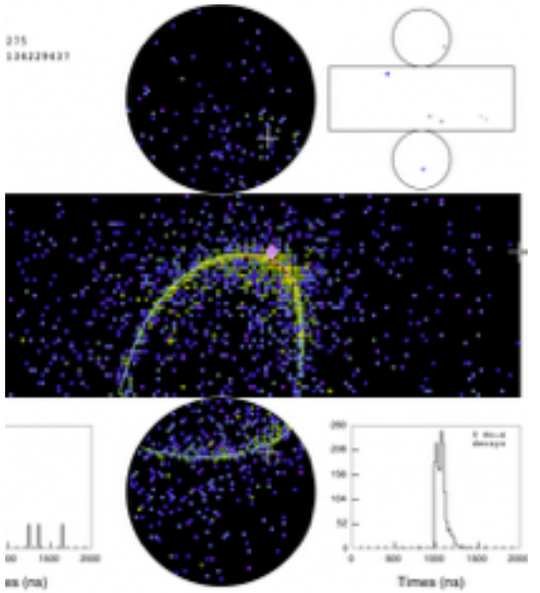
$\bar{\nu}_\mu$ to $\bar{\nu}_e$:



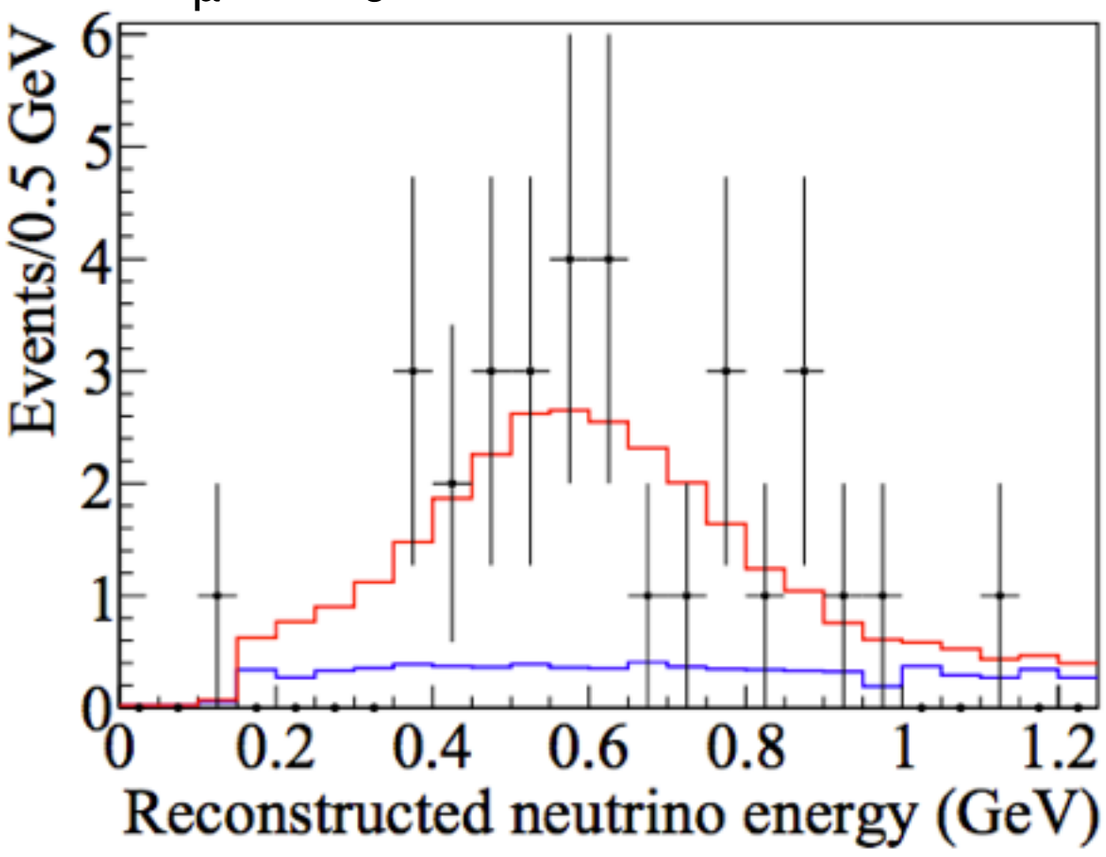
T2K Experiment

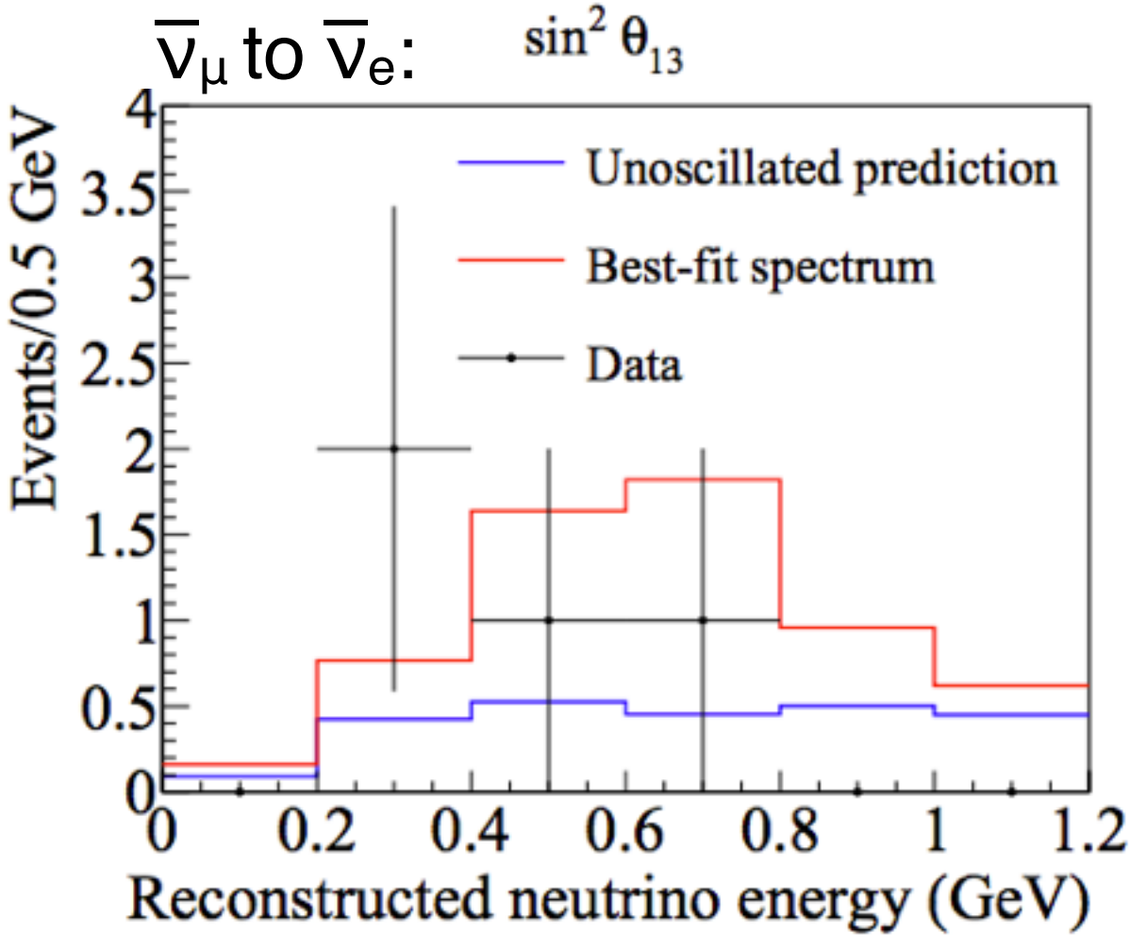




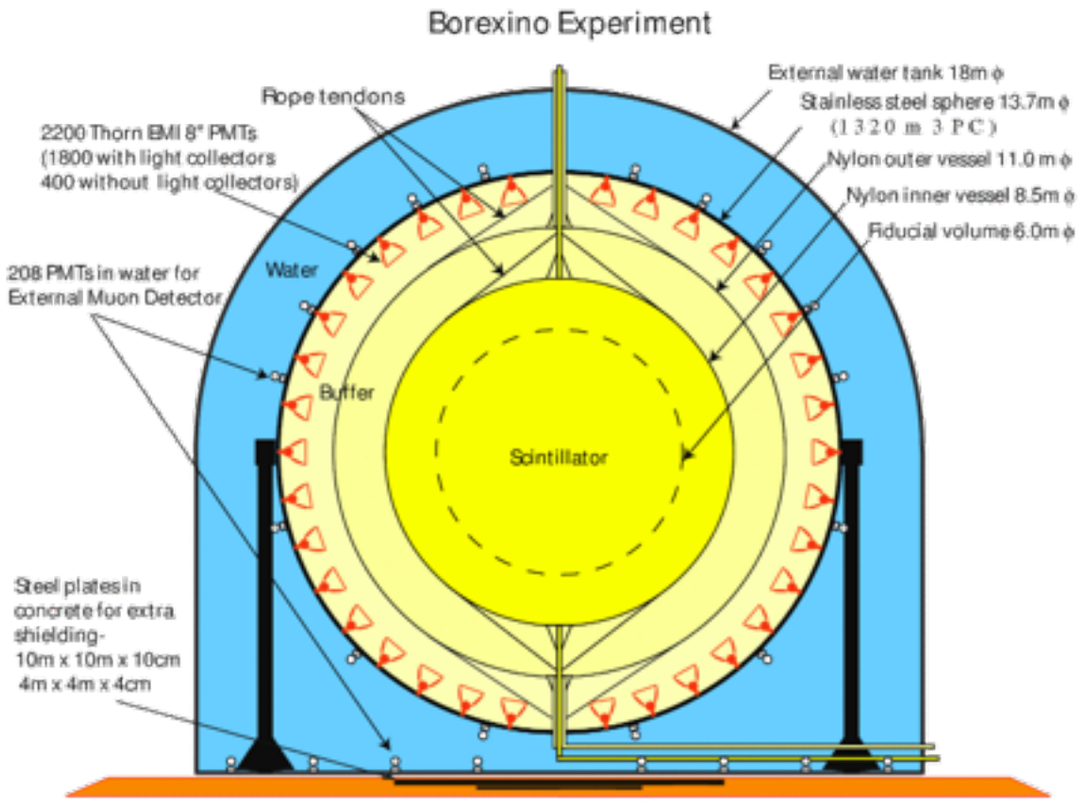


L = 295 km

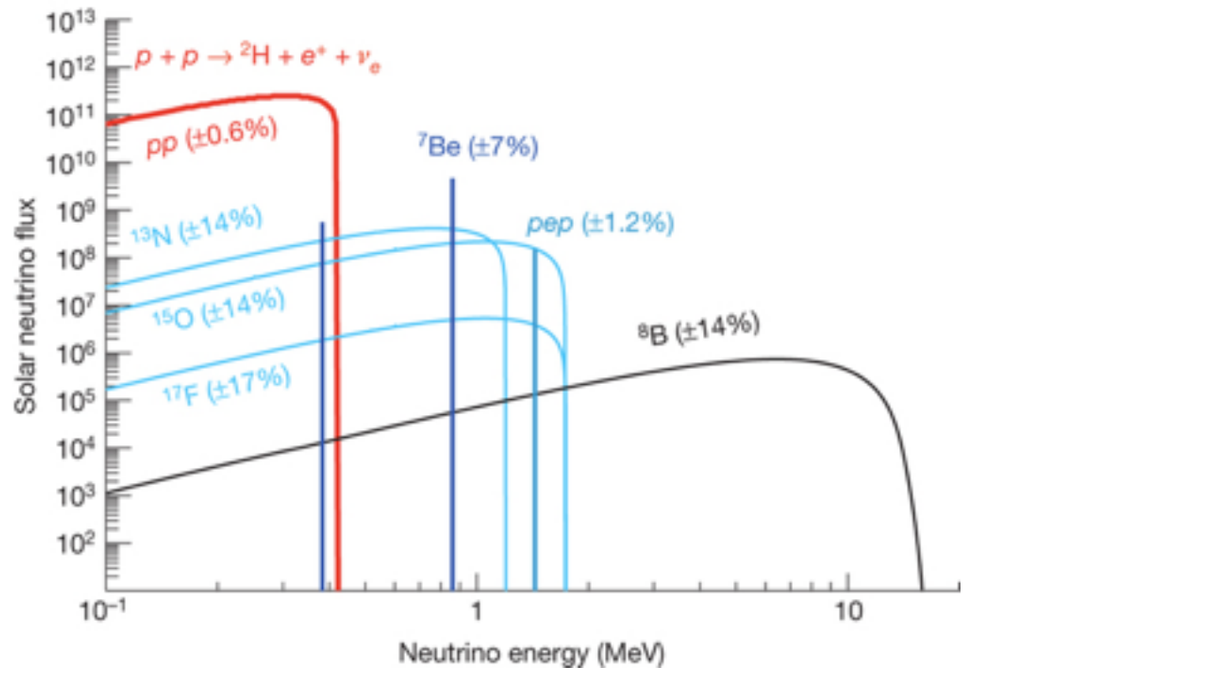




Borexino experiment

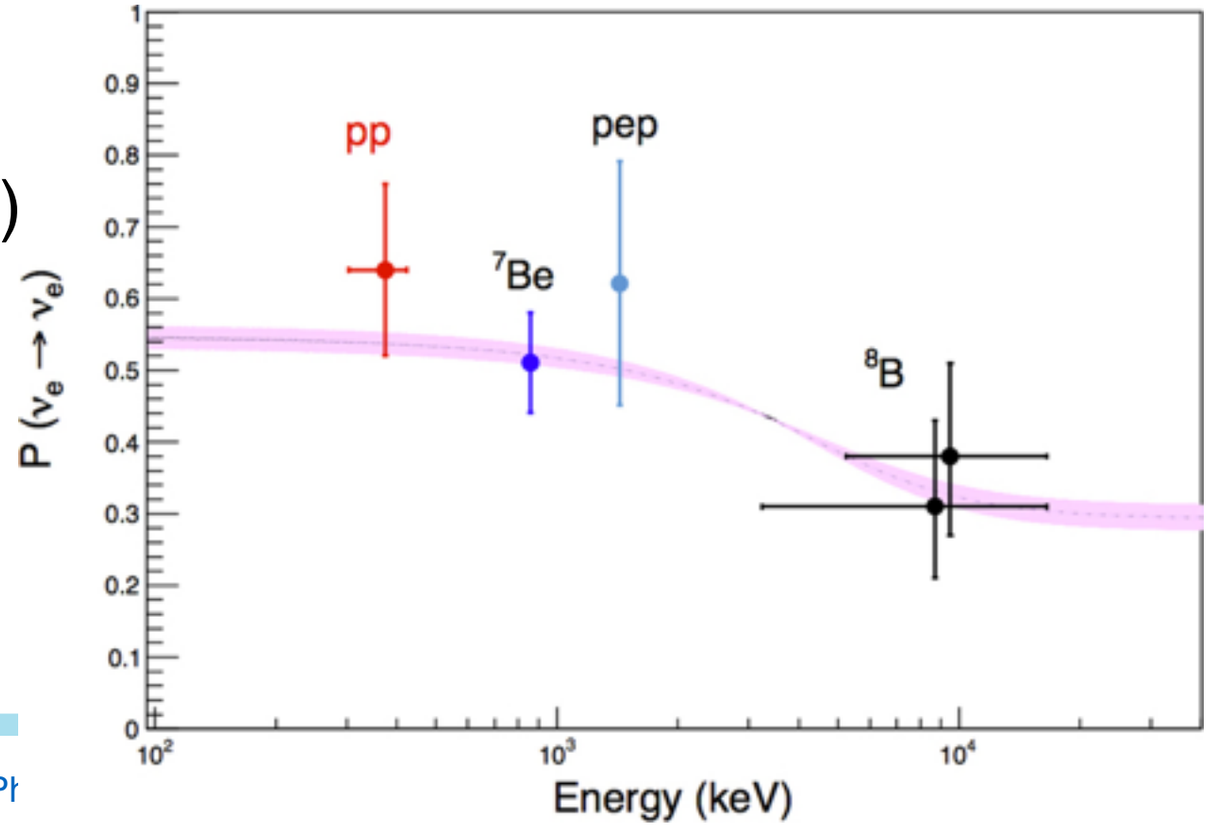


Solar neutrinos

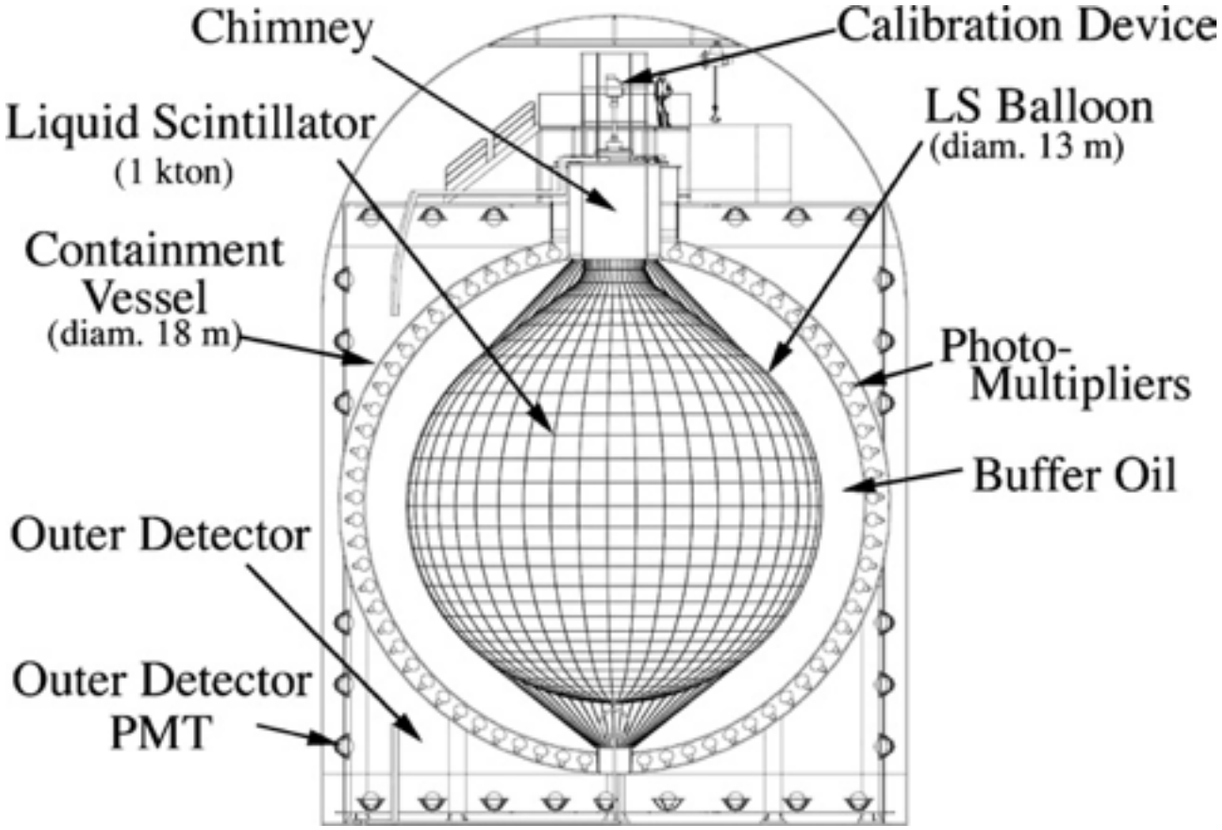


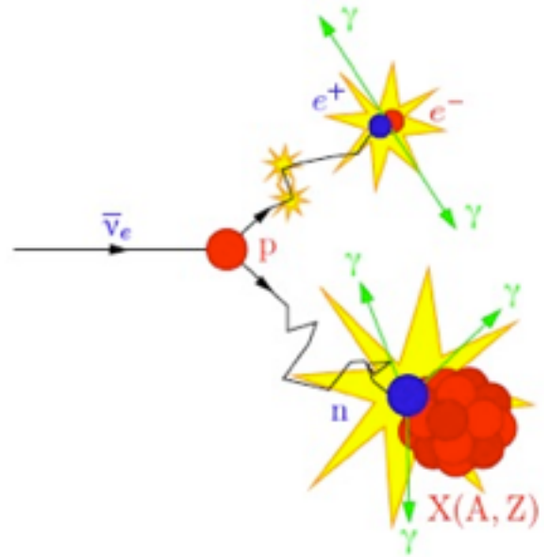
Matter effects on neutrino oscillation (MSW)

Consistent with $\Delta m^2_{sol} > 0$



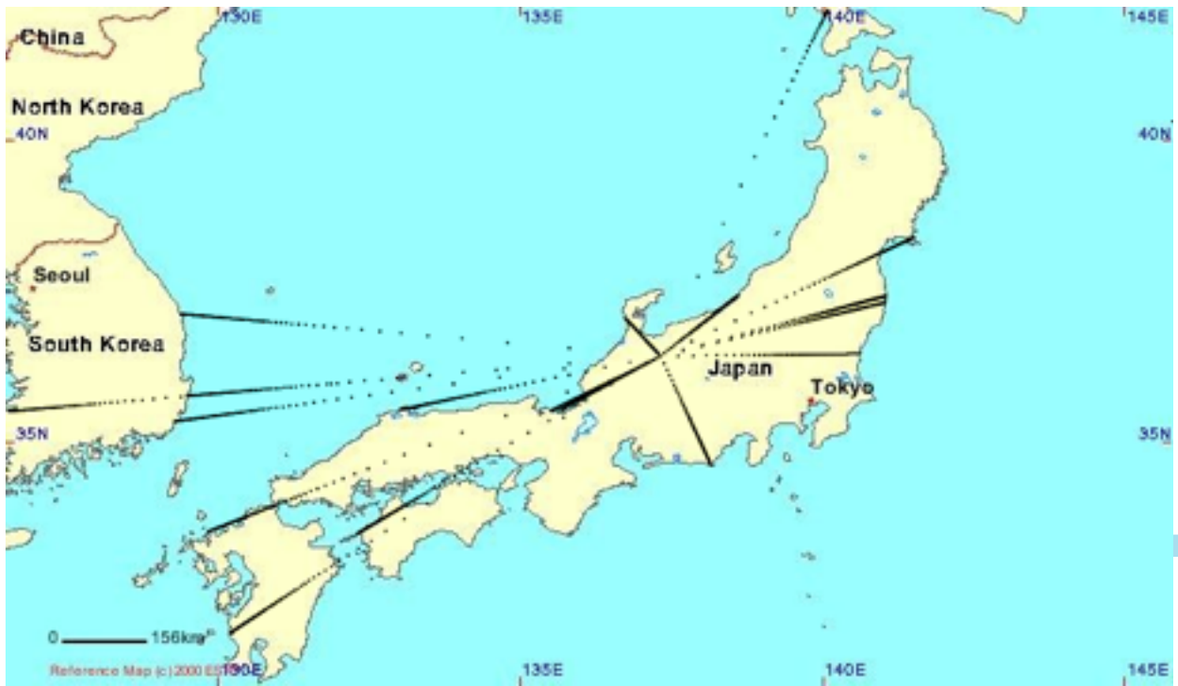
KamLAND Experiment





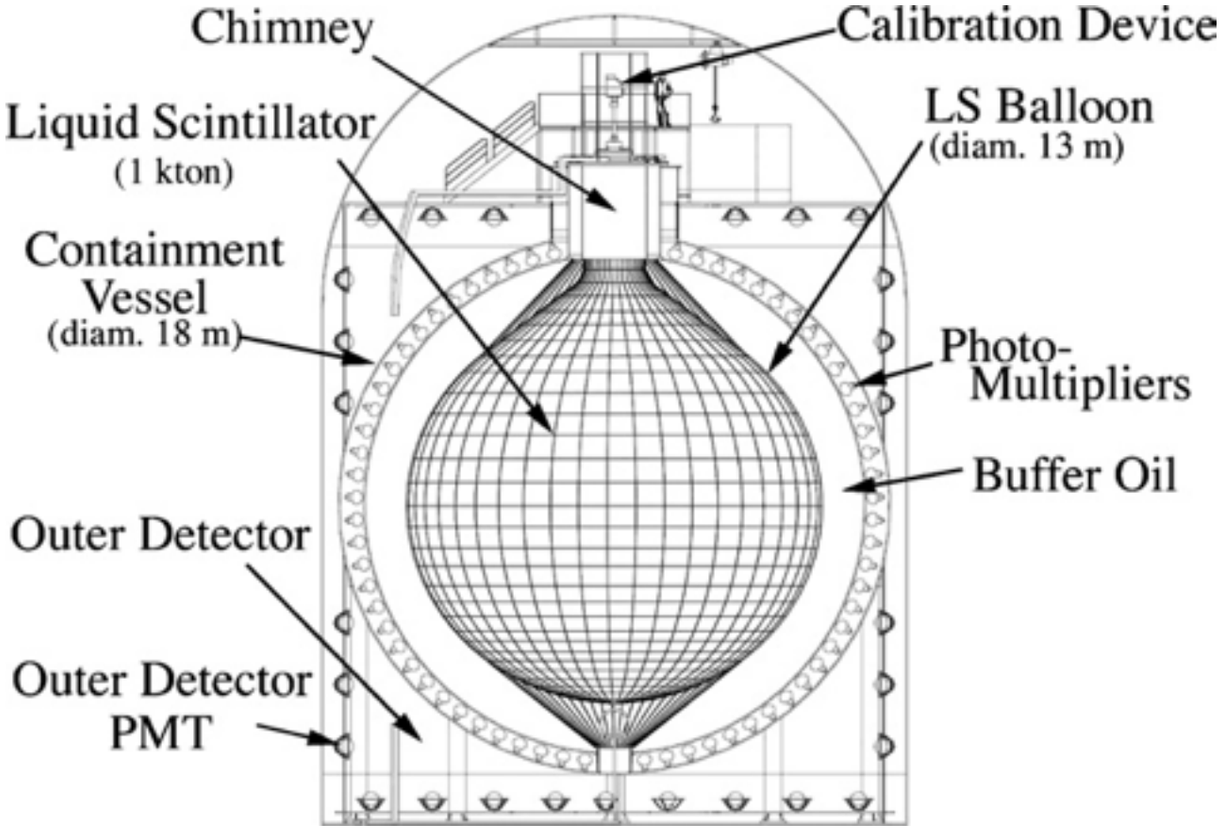
L ~ 180 km

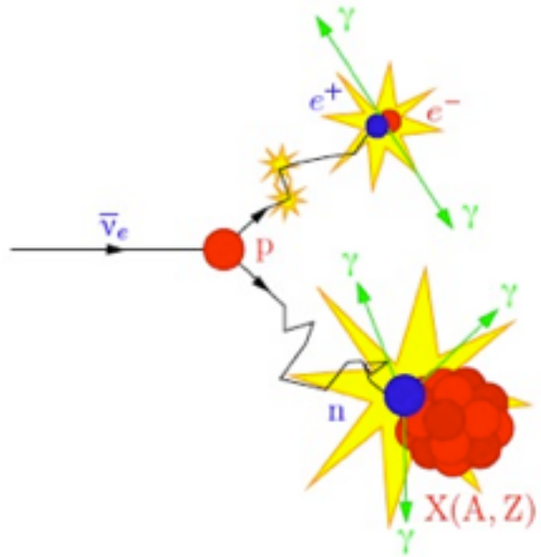
(average distance from nuclear reactor)



Fermilab
pmachado@fnal.gov

KamLAND Experiment

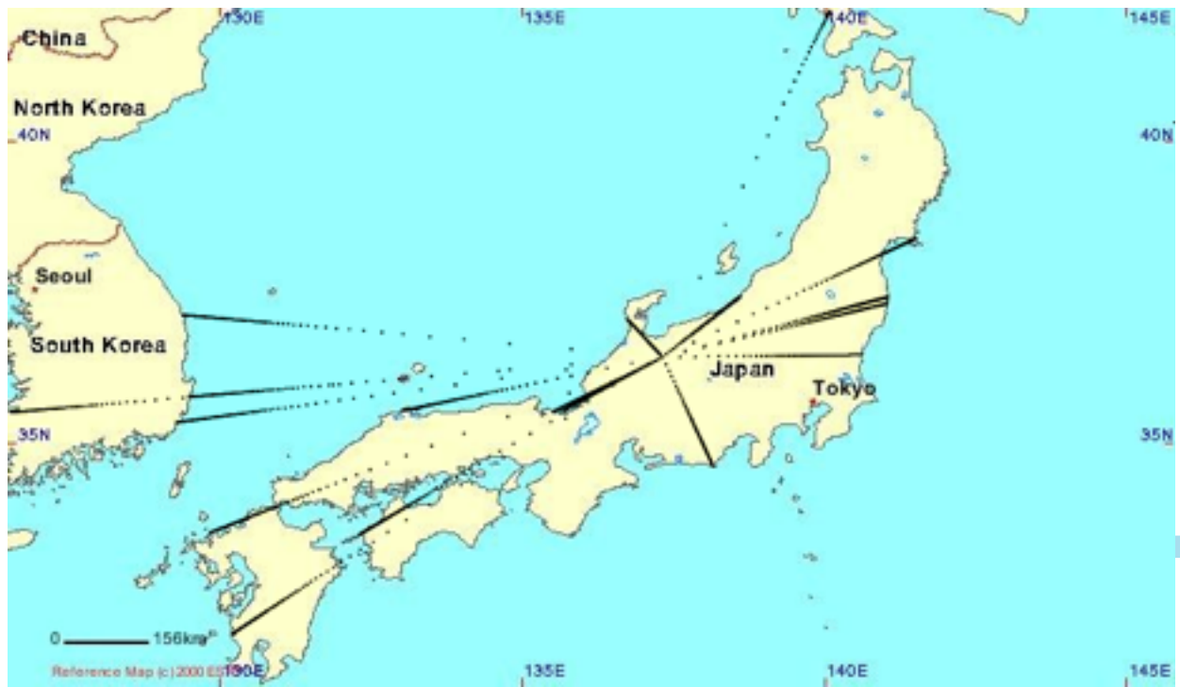


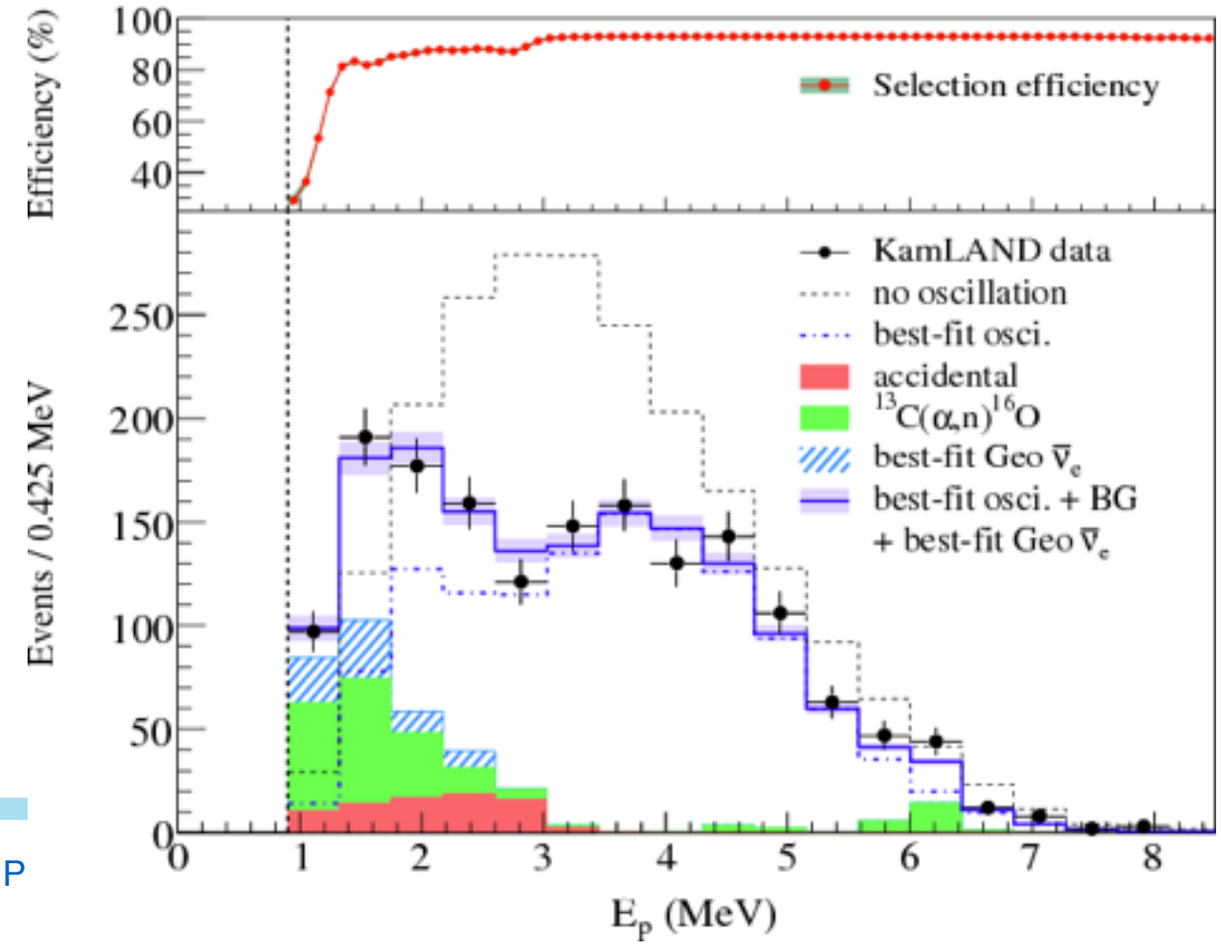


L ~ 180 km

(average distance from nuclear reactor)

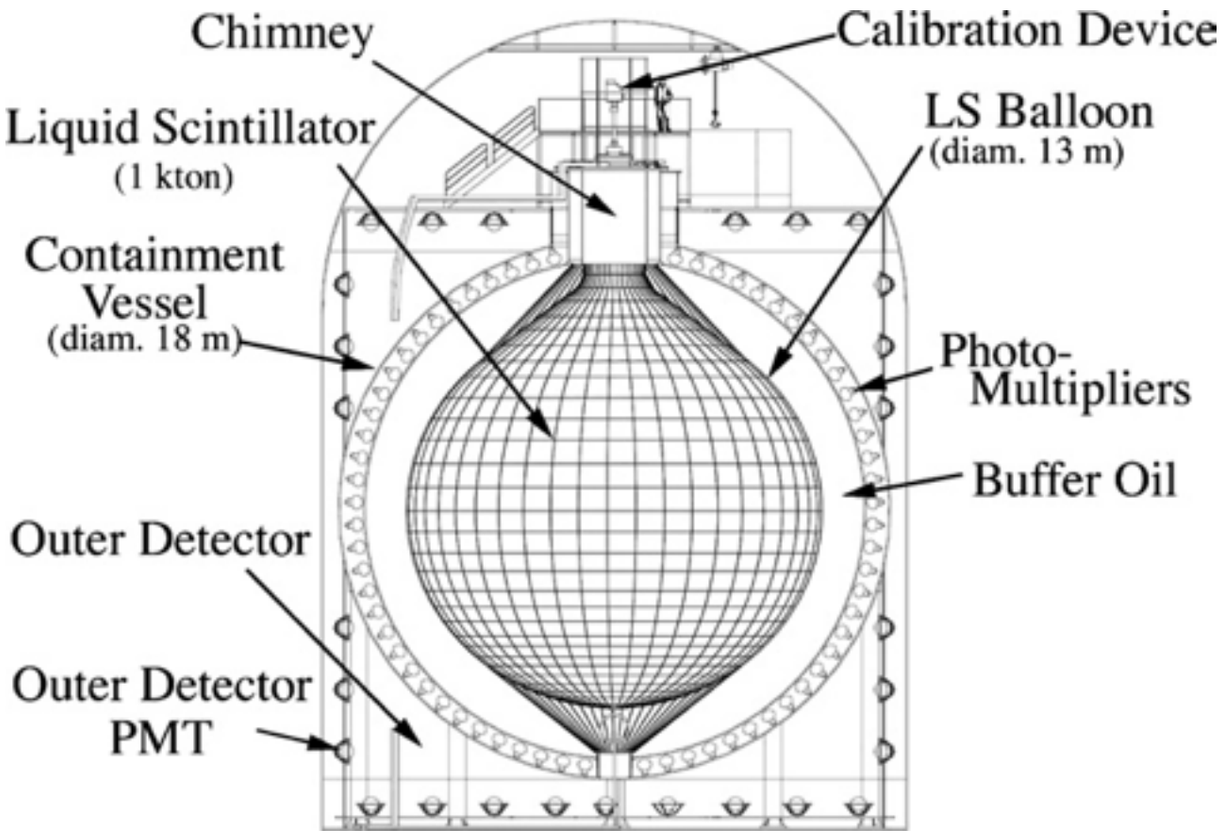
$\overline{\nu}_e$ to $\overline{\nu}_e$:

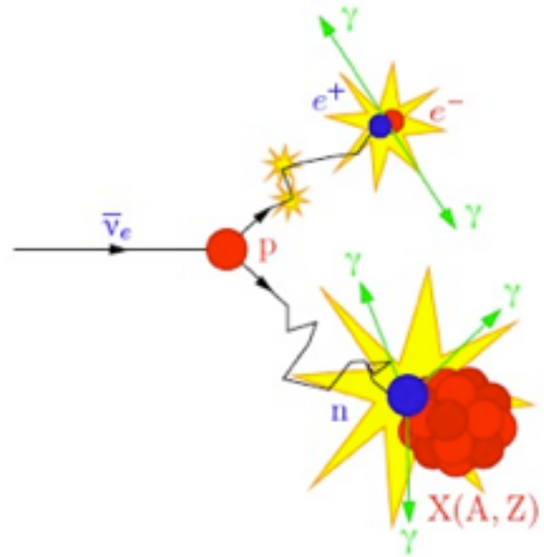




Neutrino P

KamLAND Experiment



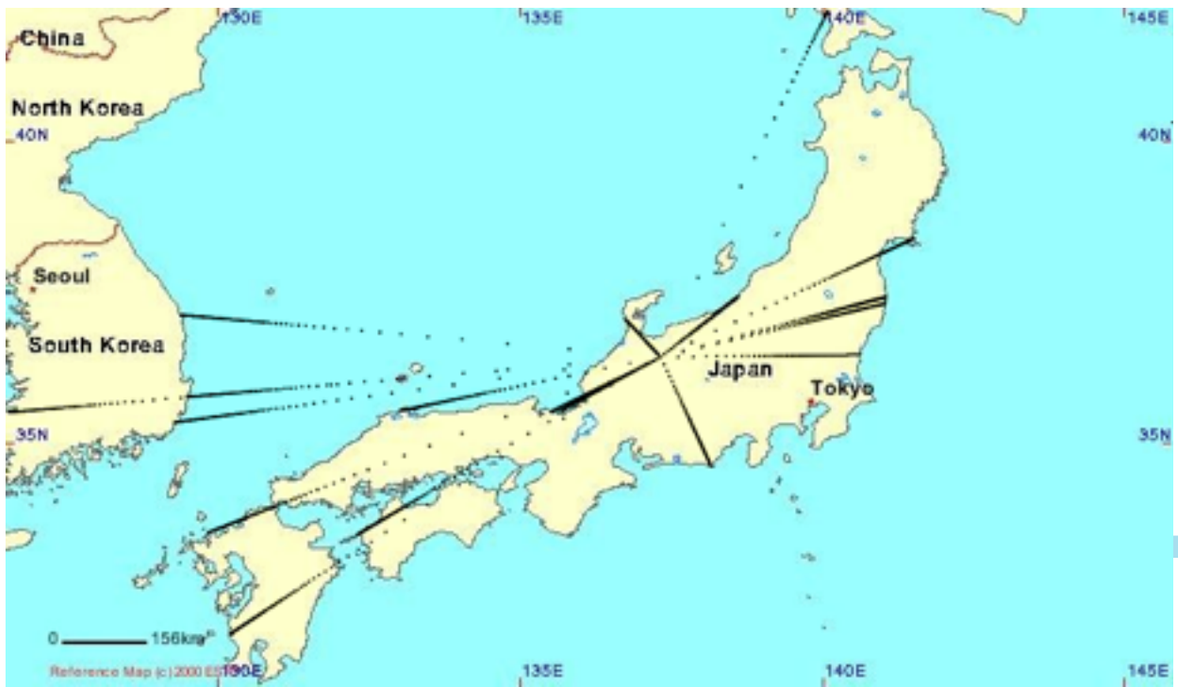


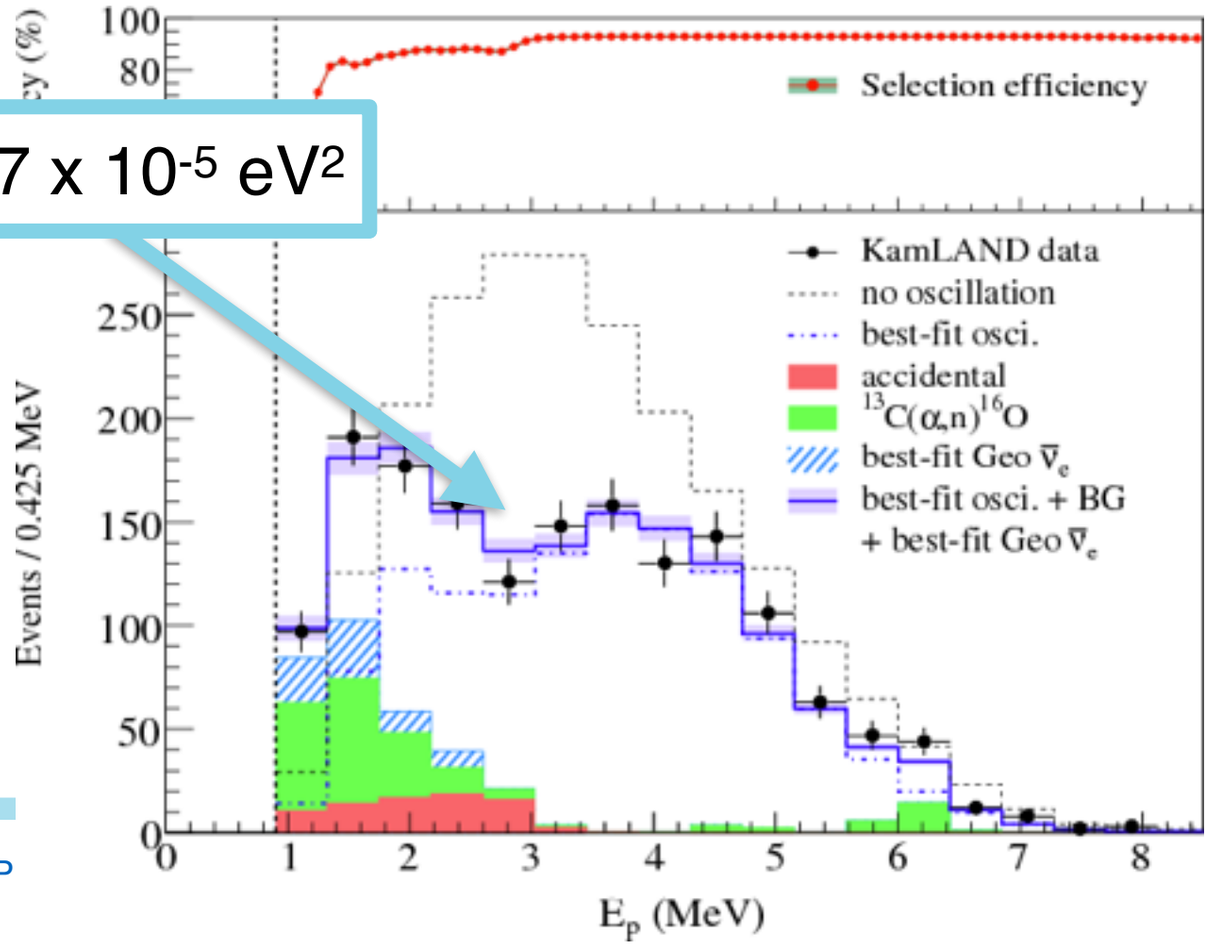
L ~ 180 km

(average distance from nuclear reactor)

$\overline{\nu}_e$ to $\overline{\nu}_e$:

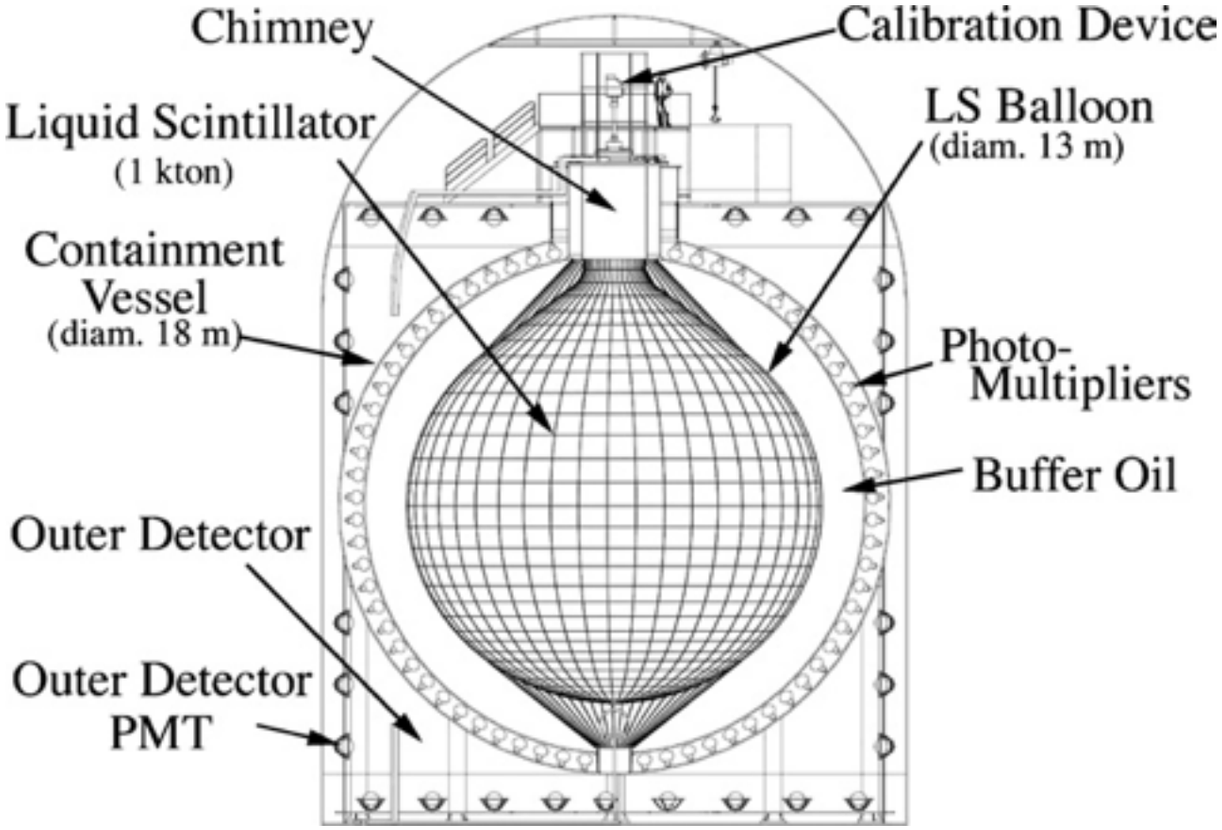
$|\Delta m^2_{sol}| \sim 7 \times 10^{-5}\ eV^2$

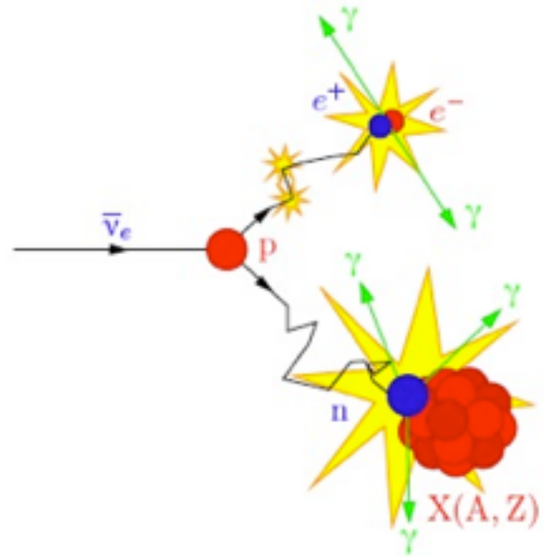




Neutrino P

KamLAND Experiment



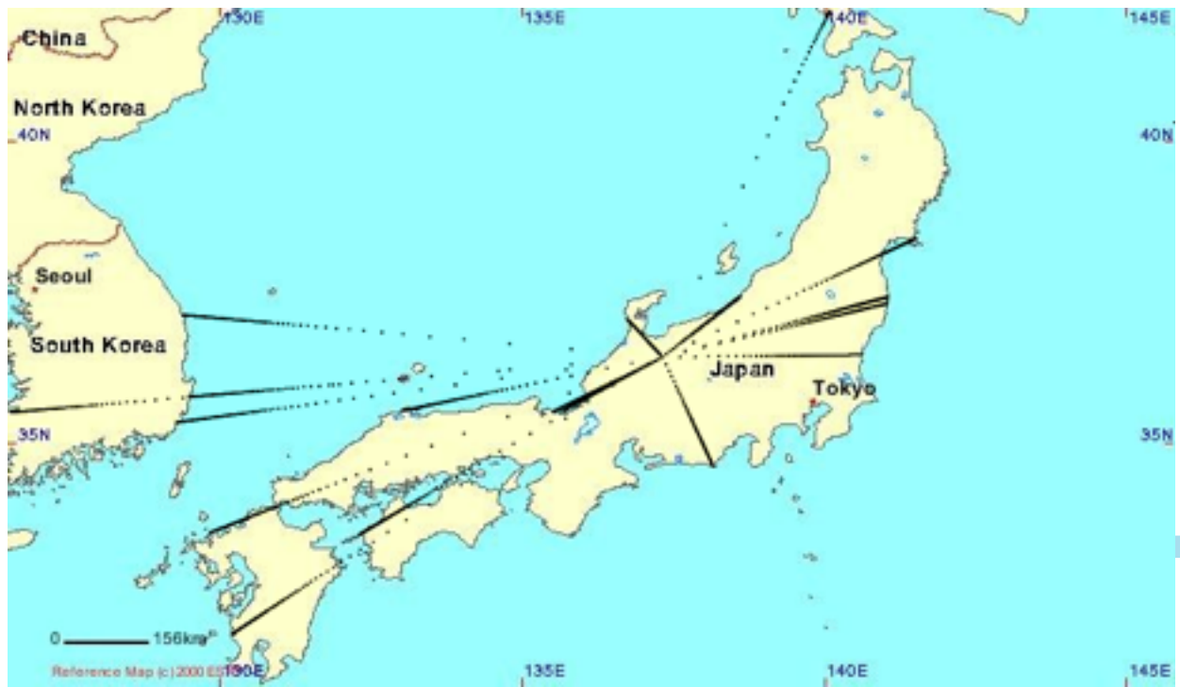


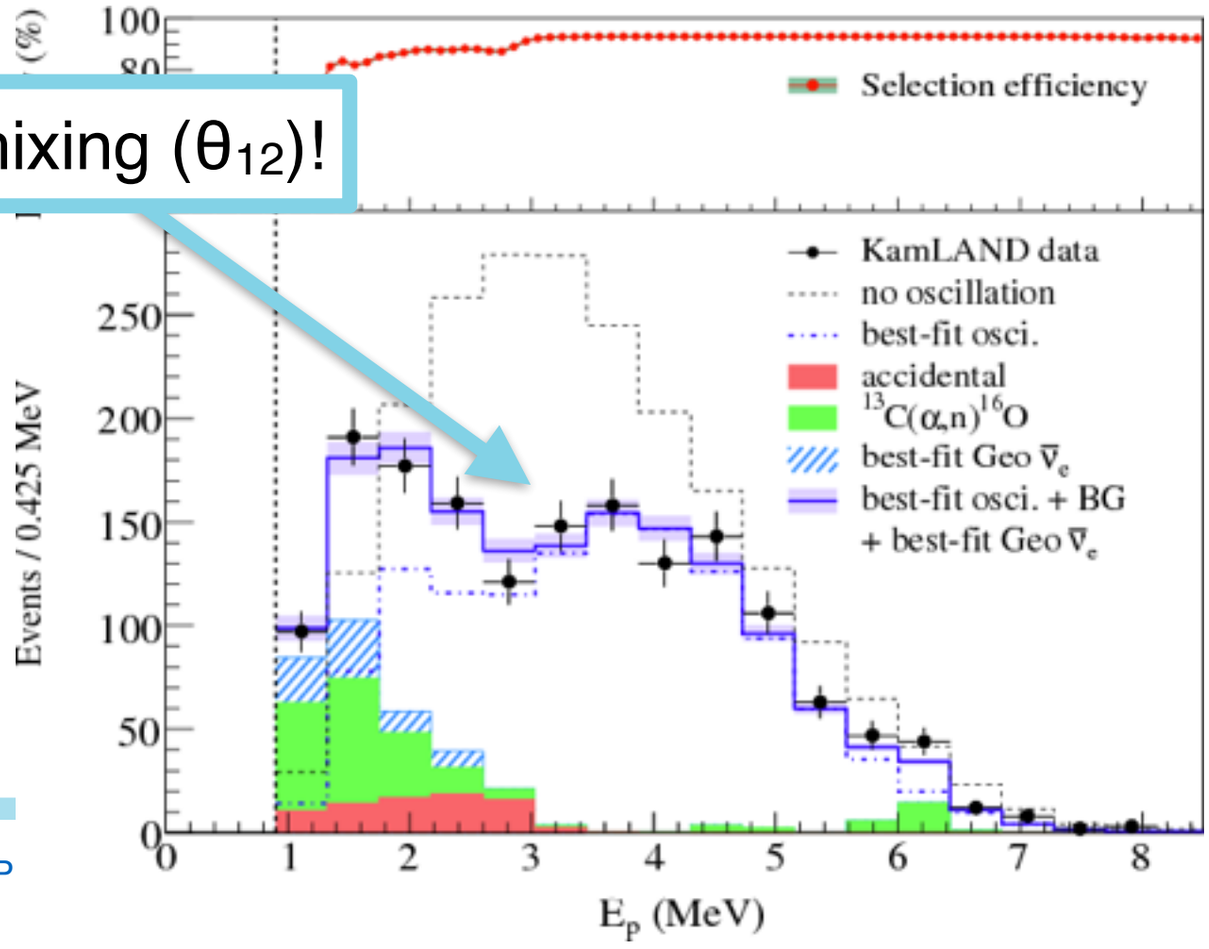
L ~ 180 km

(average distance from nuclear reactor)

$\overline{\nu}_e$ to $\overline{\nu}_e$:

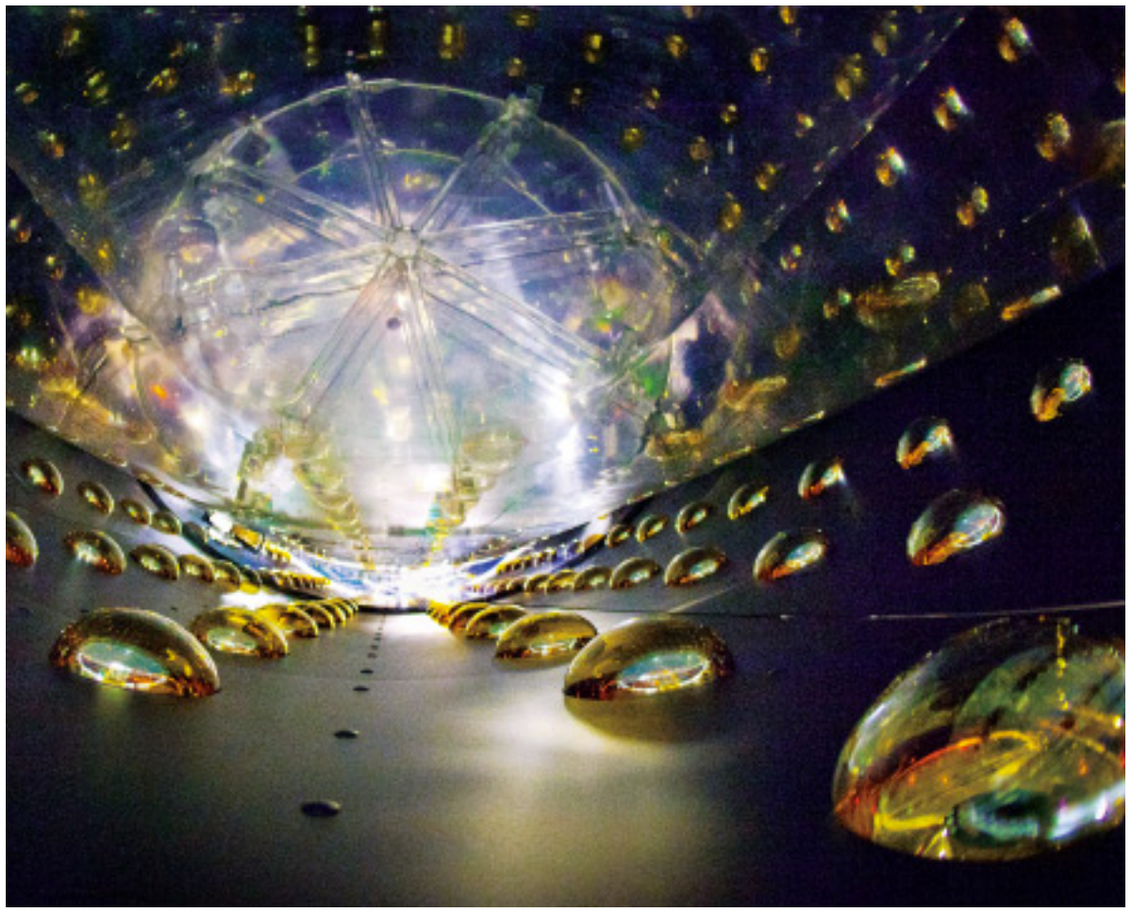
Large mixing (θ_{12})!

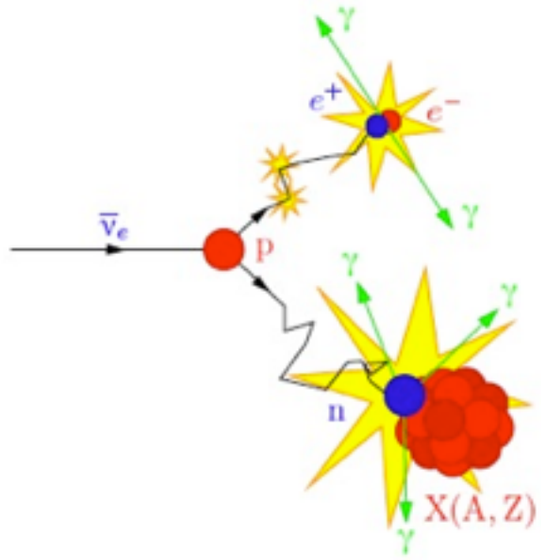




Neutrino P

Daya Bay Experiment





L between 363m and 1985m
(many detectors and many reactors)

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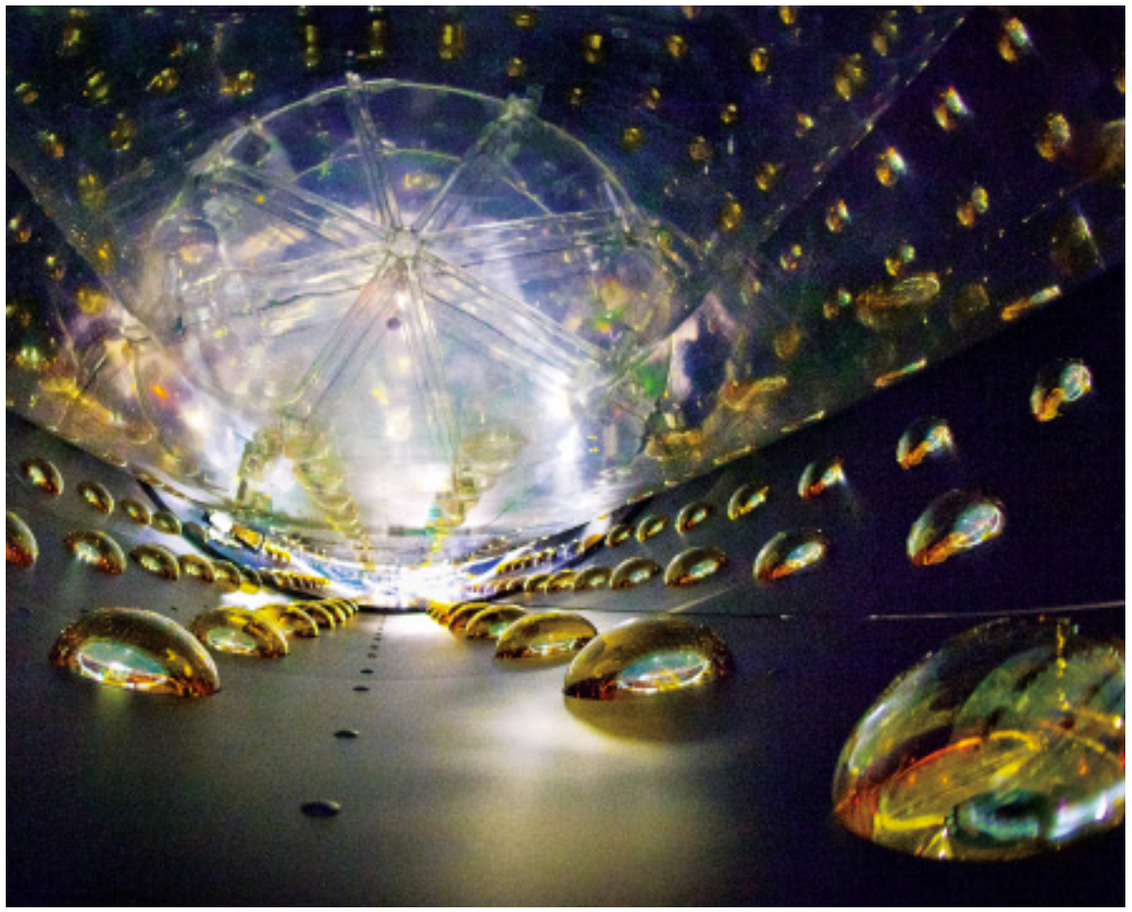
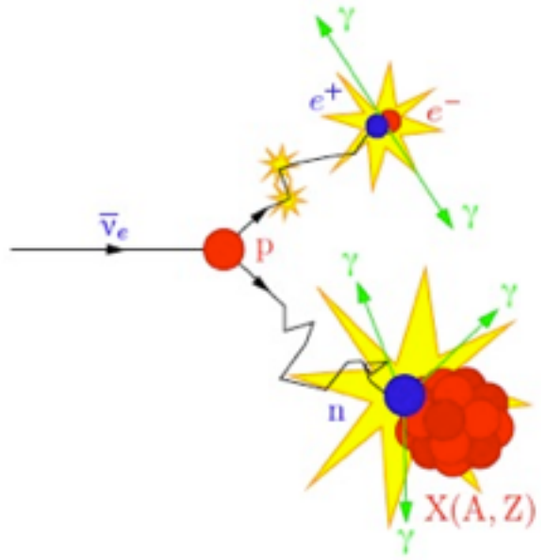
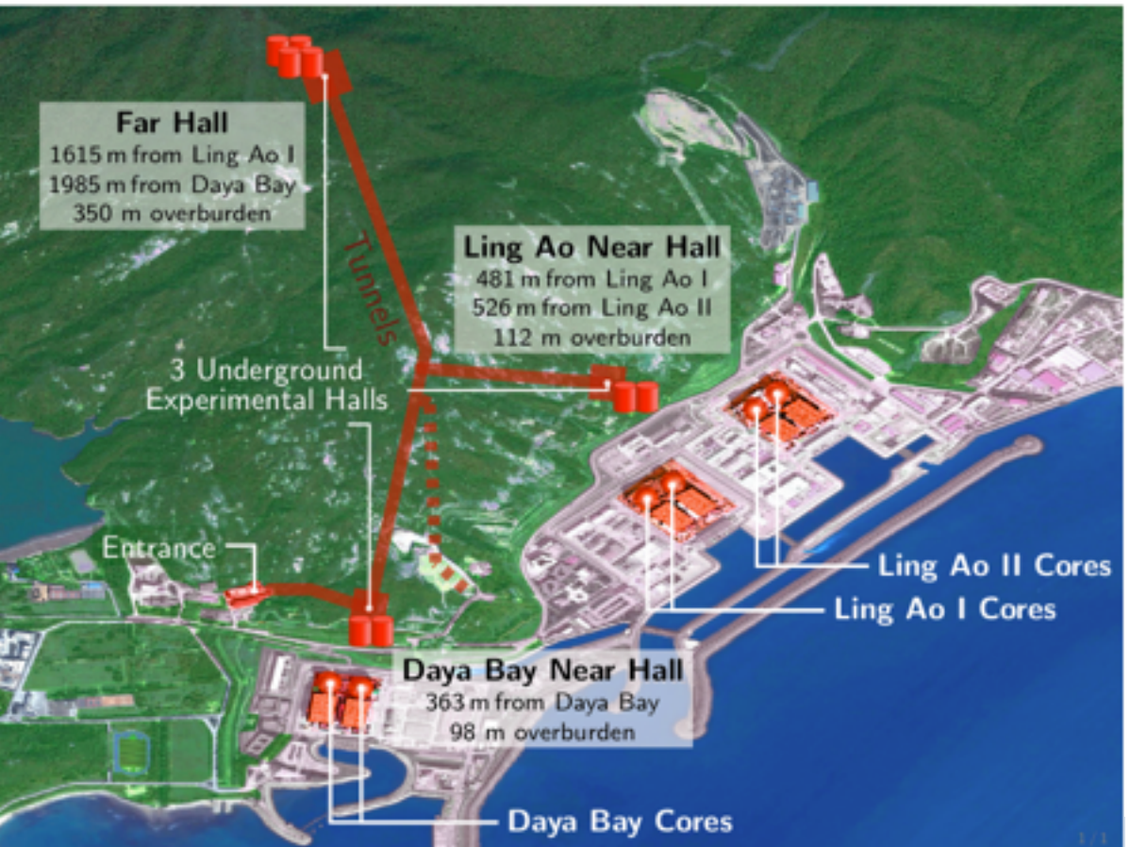
Daya Bay Experiment

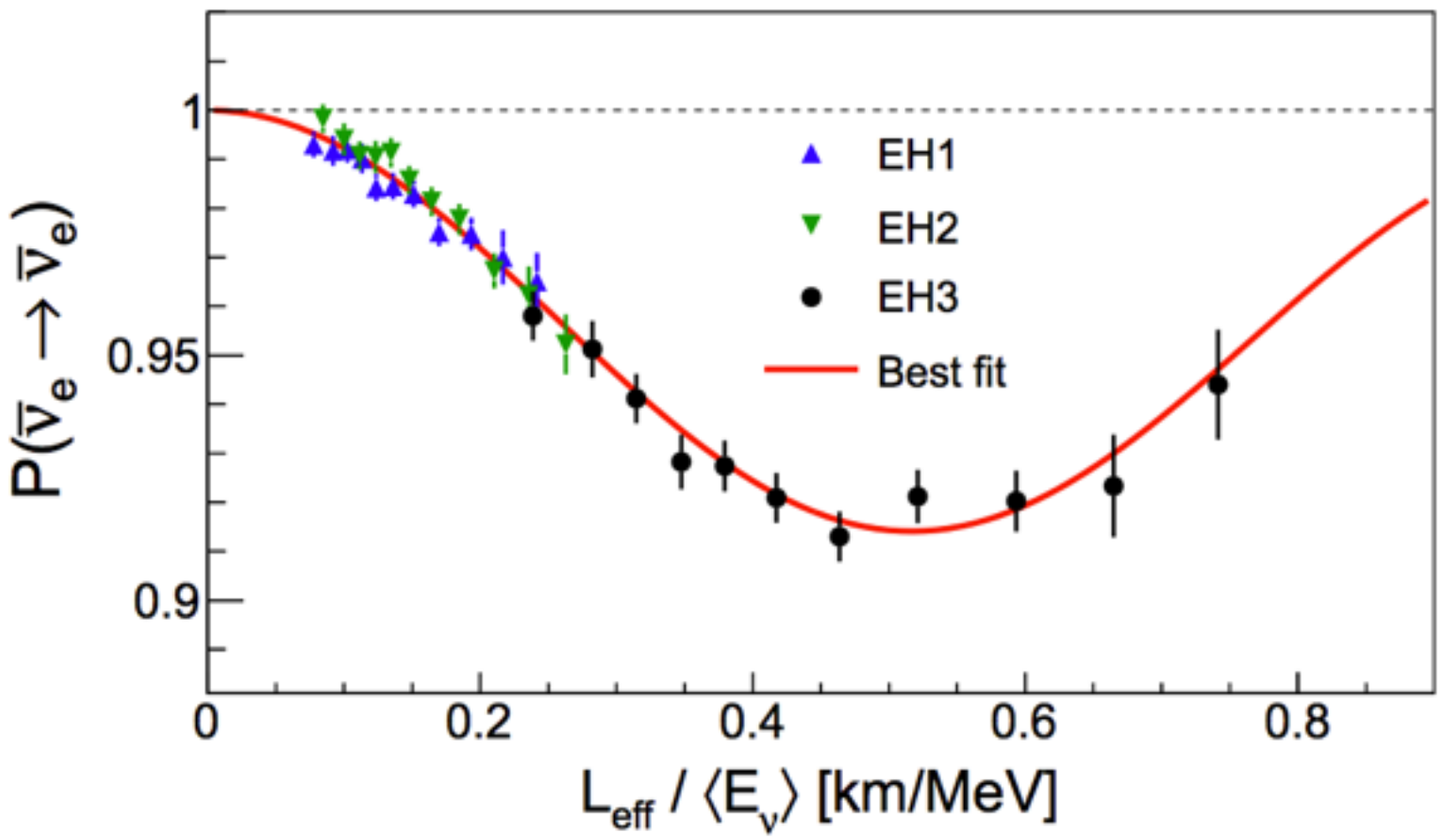




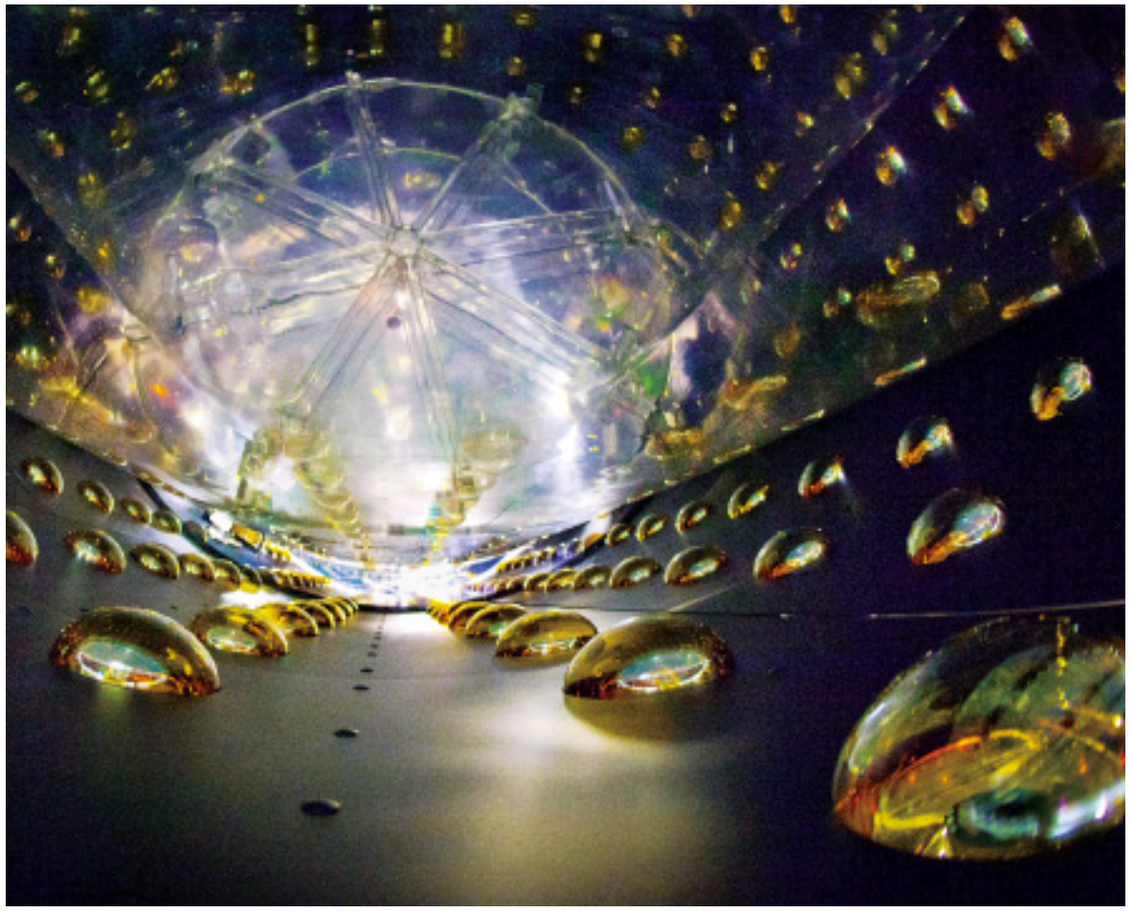
L between 363m and 1985m
(many detectors and many reactors)

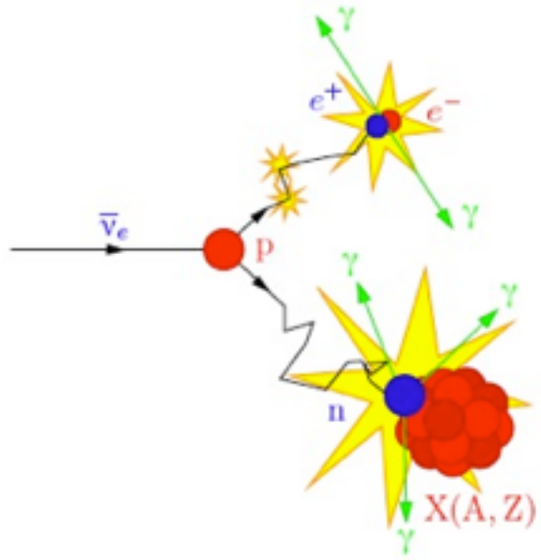


$\bar{\nu}_e$ to $\bar{\nu}_e$:

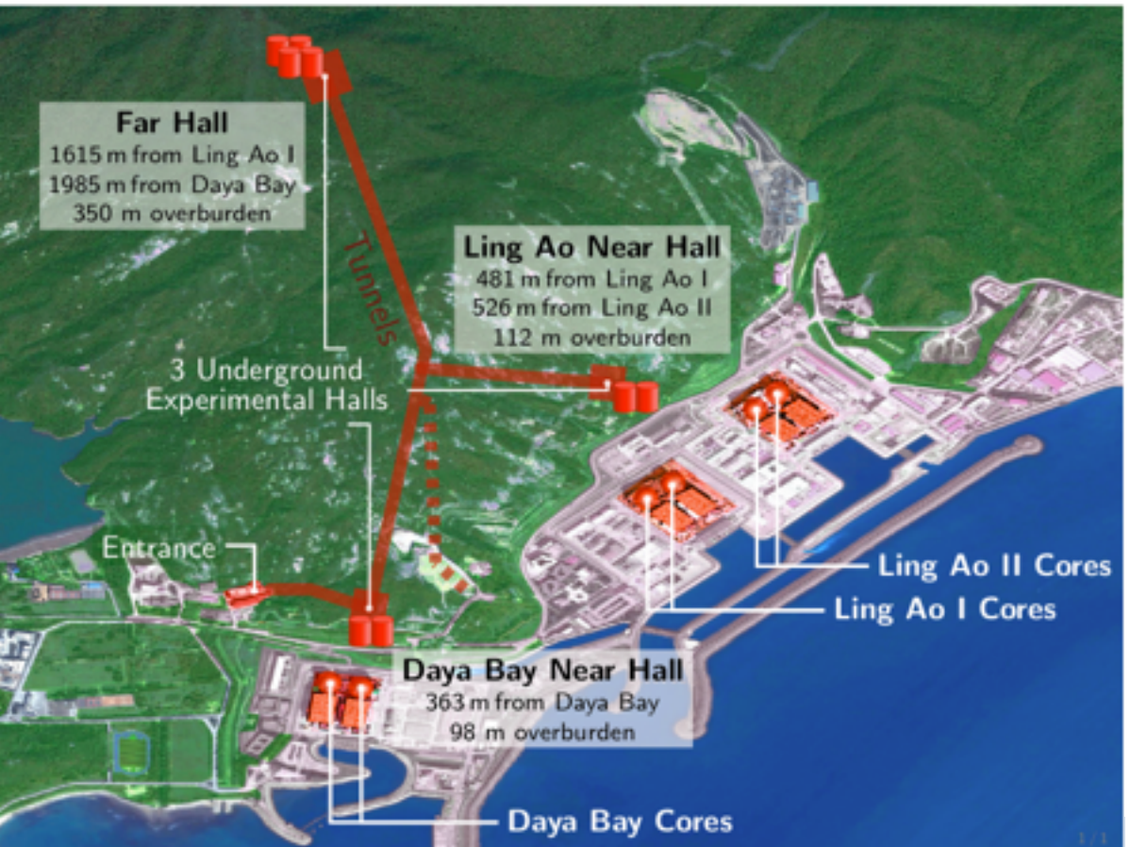


Daya Bay Experiment

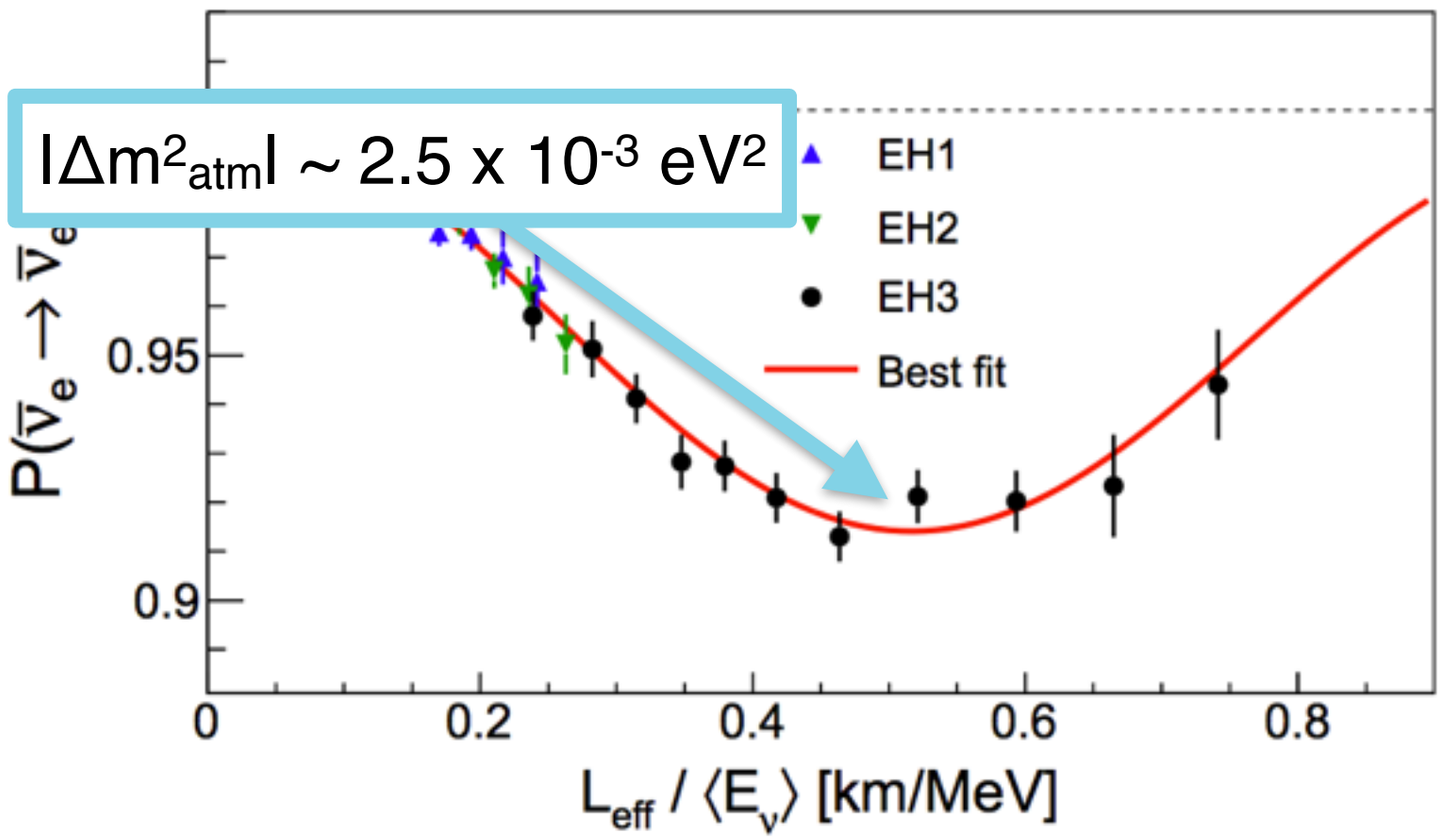




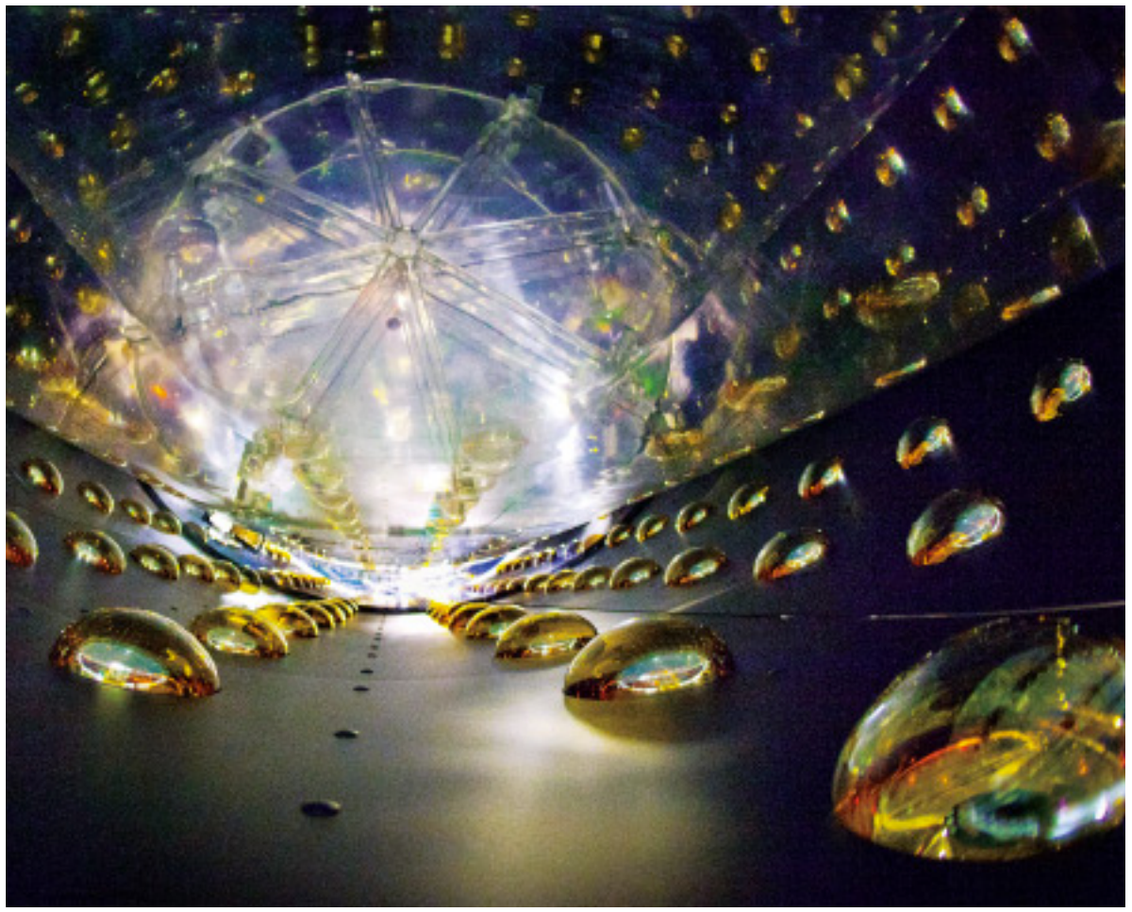
L between 363m and 1985m
(many detectors and many reactors)

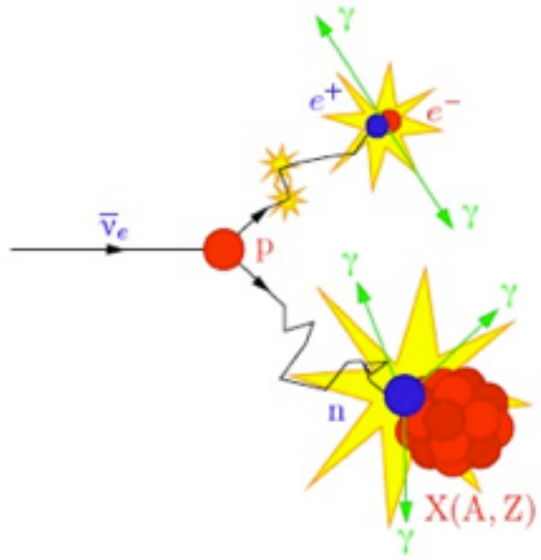


$\overline{\nu}_e$ to $\overline{\nu}_e$:

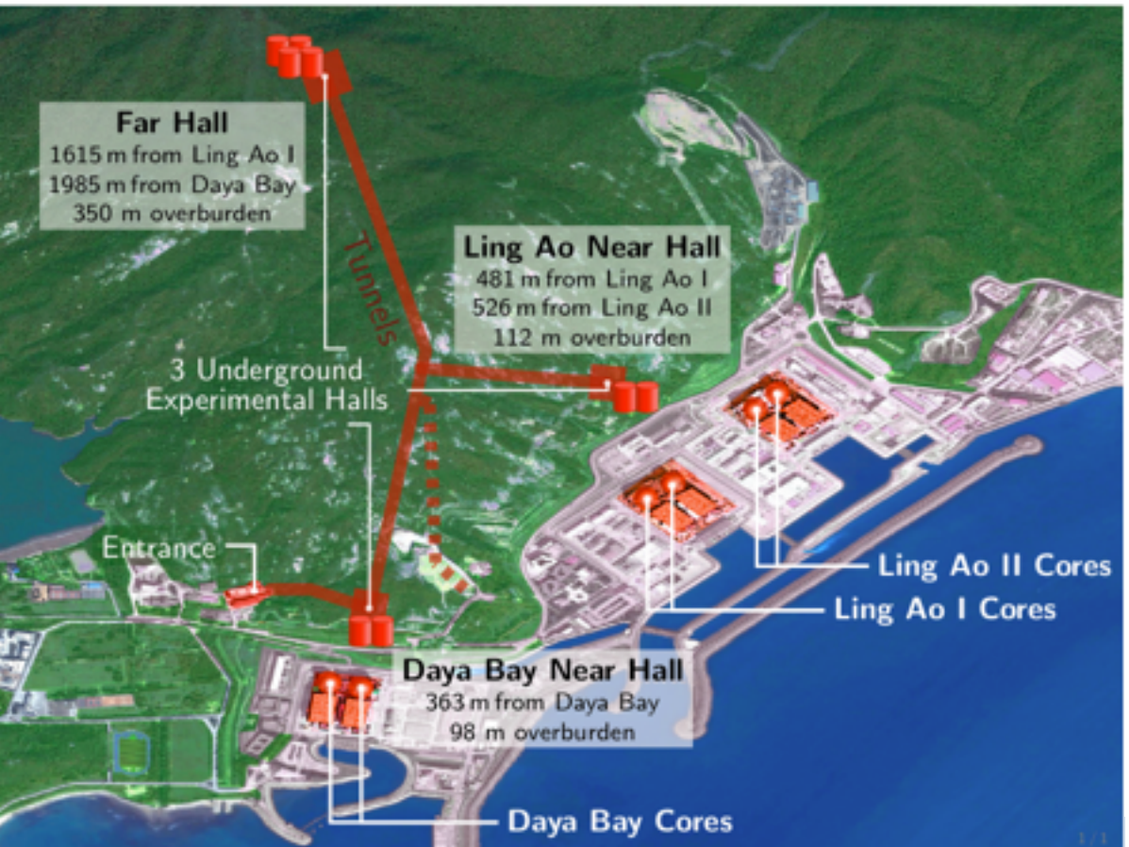


Daya Bay Experiment

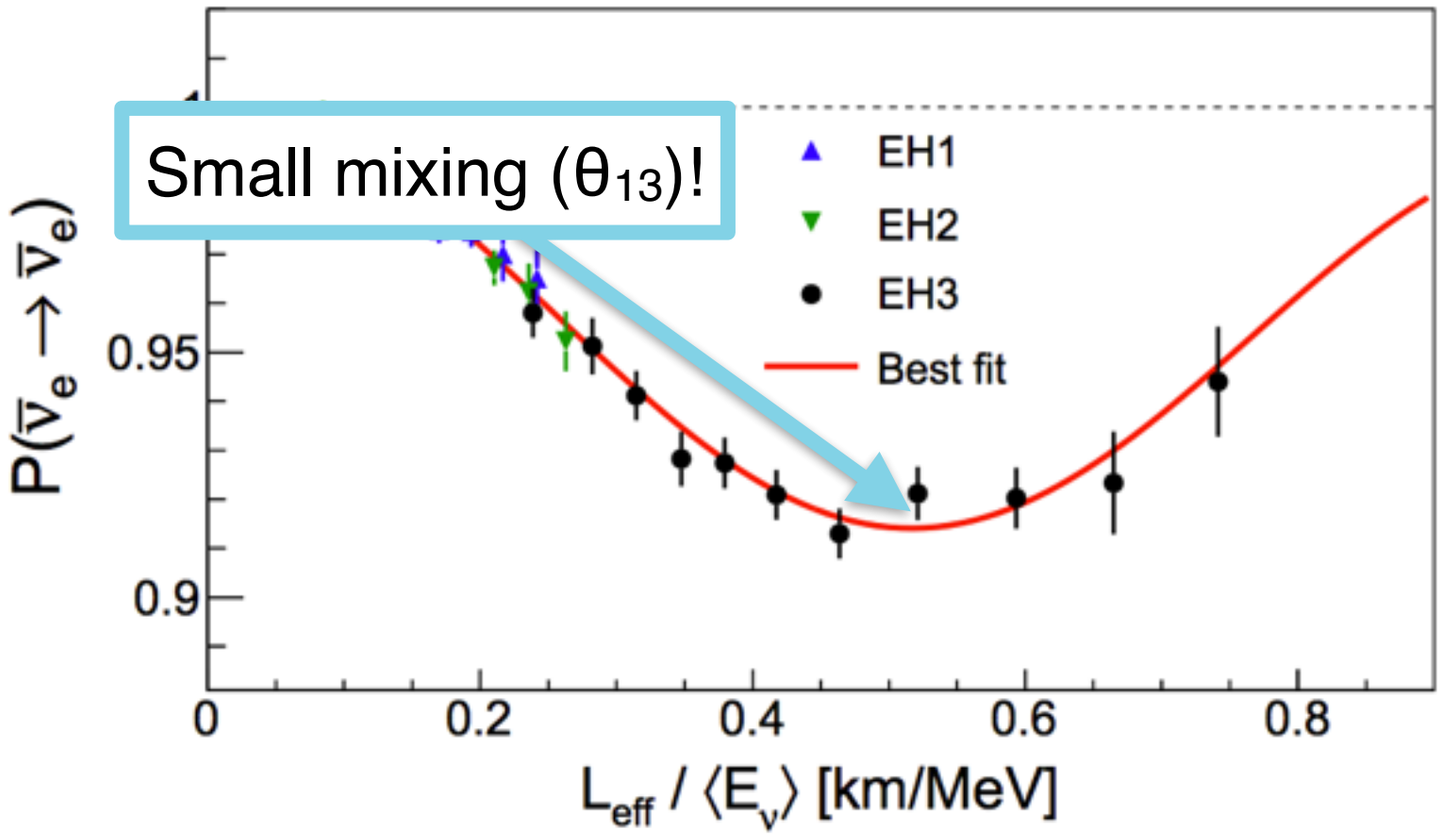




L between 363m and 1985m
(many detectors and many reactors)



$\bar{\nu}_e$ to $\bar{\nu}_e$:



Many Experiments

MINOS/MINOS+ FNAL, accelerator nus, atmospheric parameters

LSND LANL, accelerator nus, anomalous Δm^2 (too large)

MiniBooNE FNAL, accelerator nus, anomalous Δm^2 (too large)

MicroBooNE FNAL, accelerator nus, complementary to MiniBooNE

Minerva FNAL, accelerator nus, nu-nucleus cross section measurements

ICARUS LNGS, accelerator nus, atmospheric parameters

OPERA LNGS, accelerator nus, atmospheric parameters (ν_μ to ν_τ oscillations)

SNO Sudbury, solar neutrinos

Super Kamiokande Japan, atmospheric nus, atmospheric parameters

RENO Korea, reactor neutrinos, atmospheric parameters

Double Chooz France, reactor neutrinos, atmospheric parameters

...

Many Experiments

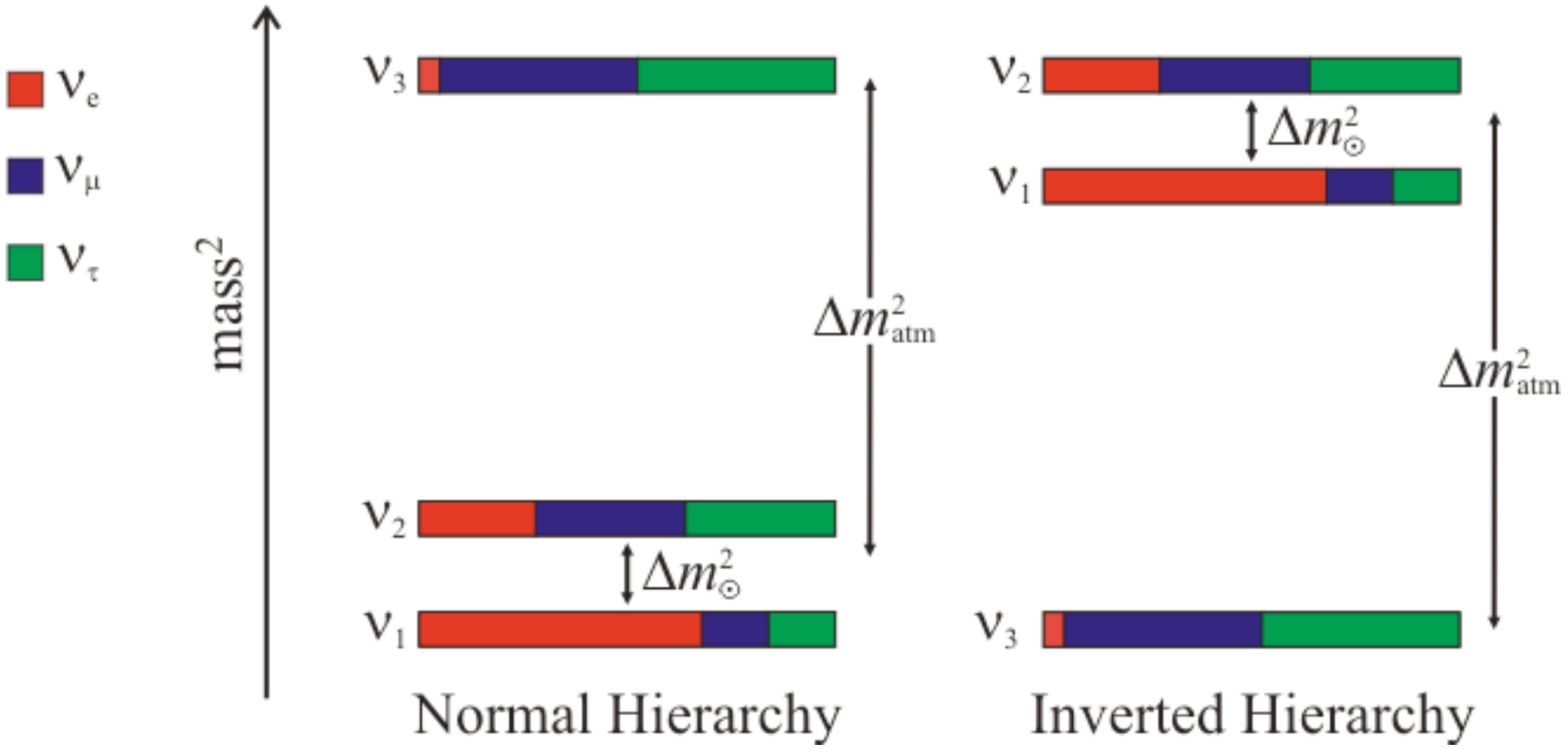
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\rm CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

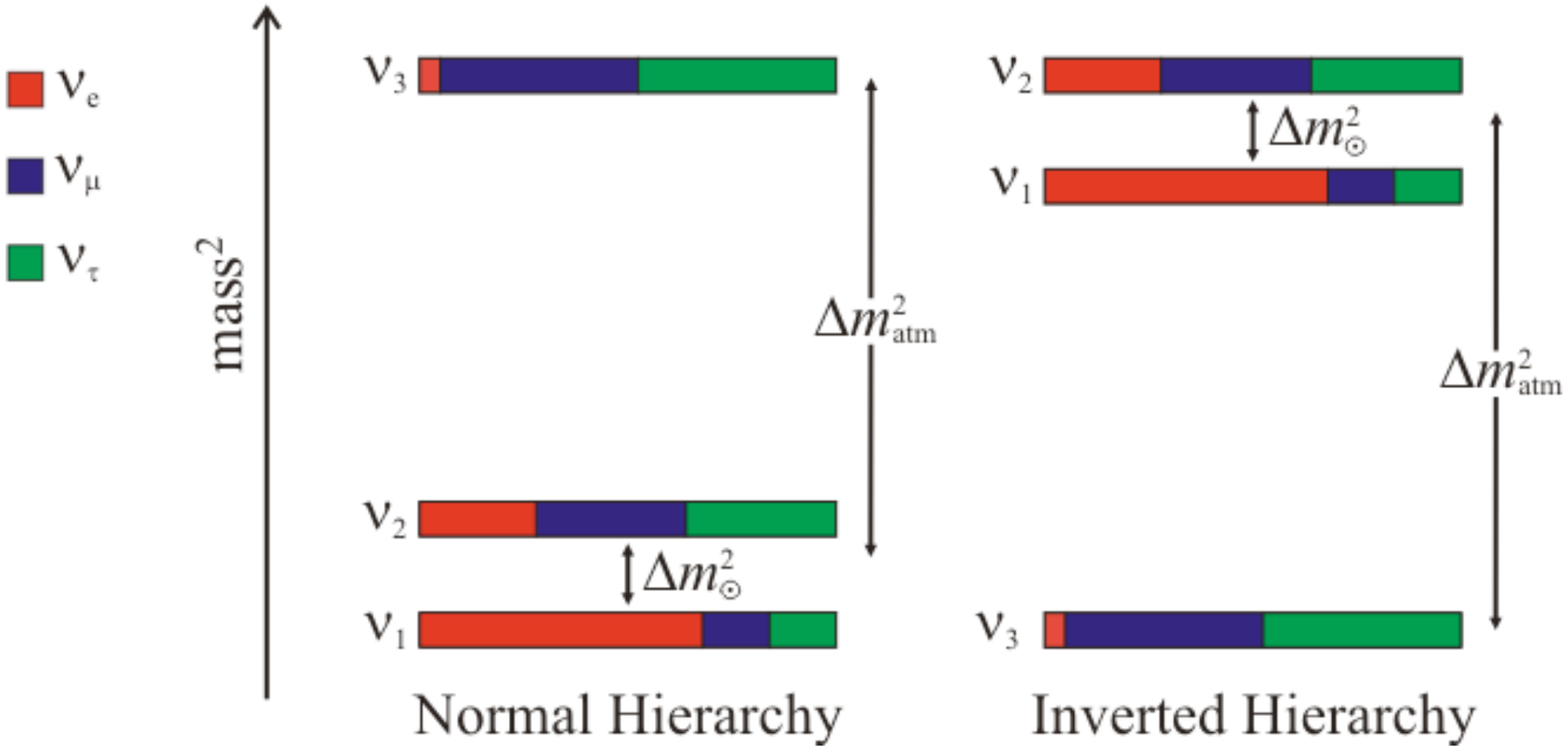
Open questions

What is the mass ordering?



Open questions

What is the mass ordering?



Is there CP violation in the lepton sector?

What is the octant of θ_{23}?

Or:

Is there more ν_μ or ν_τ in ν_2?

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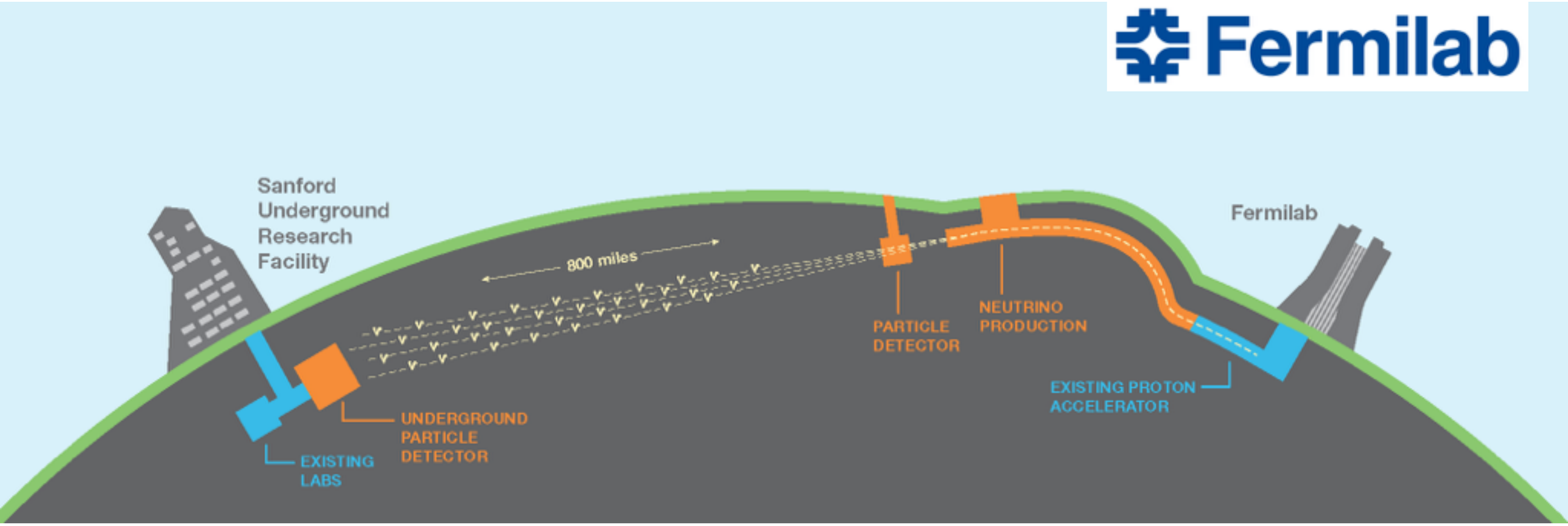
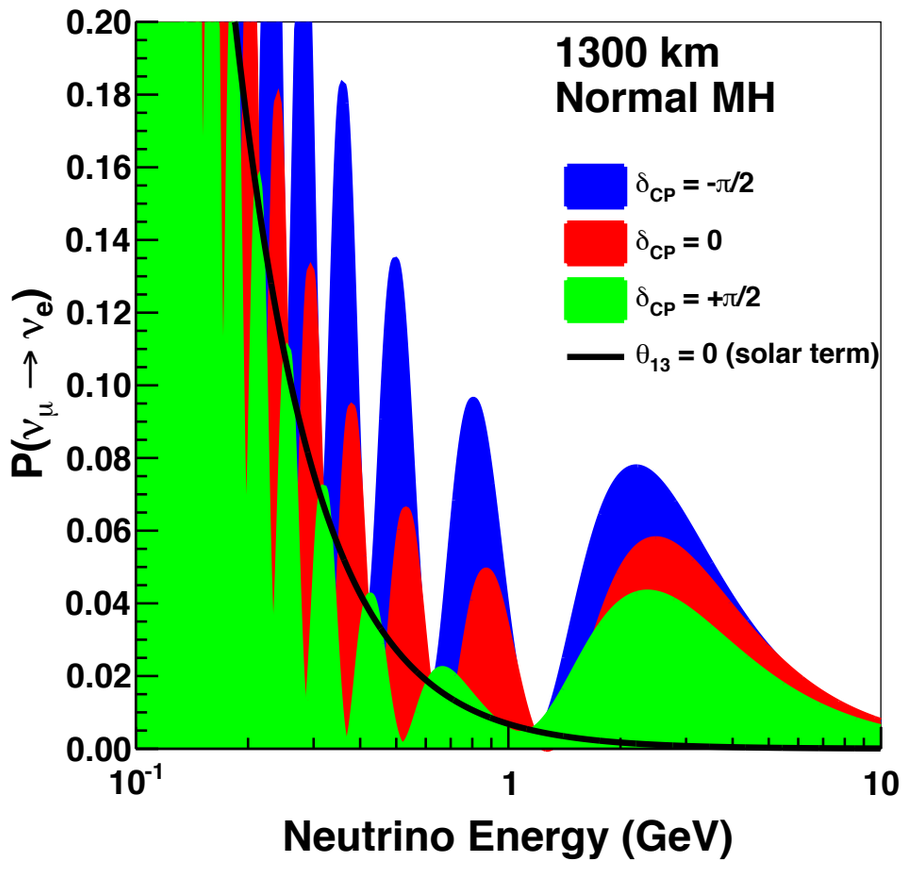
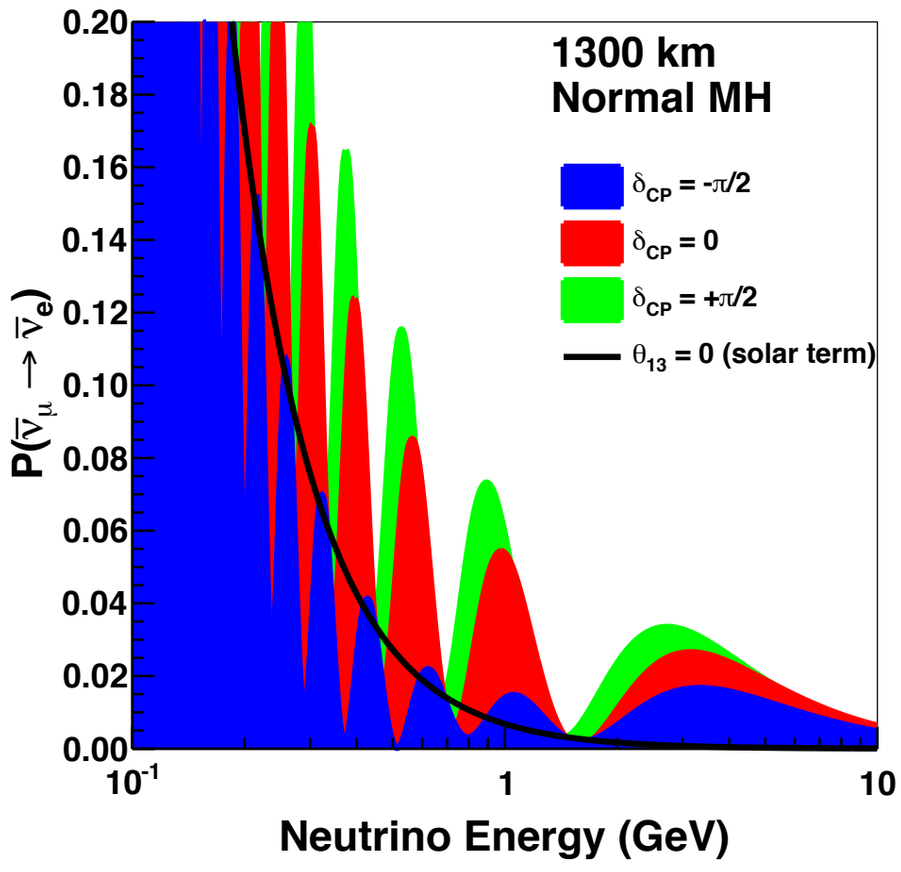
Open questions







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Open questions

Are neutrinos Dirac or Majorana?

Or:

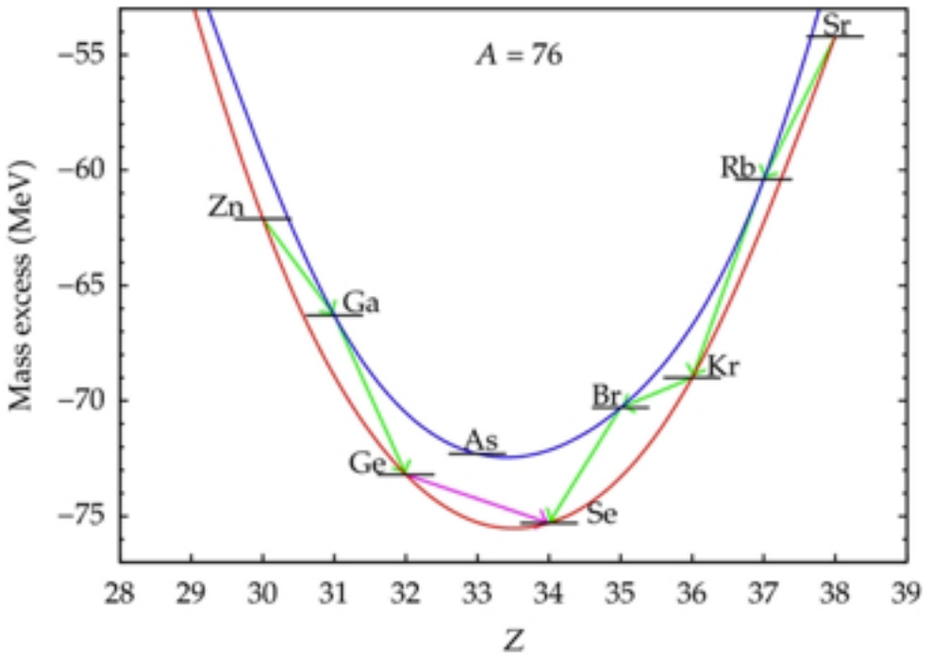
Are neutrinos their own antiparticle?

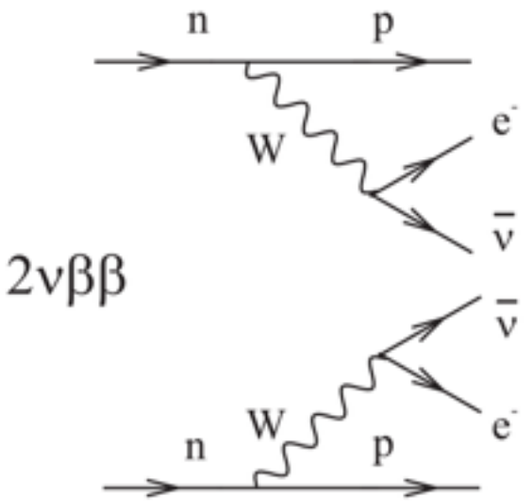
Open questions

Are neutrinos Dirac or Majorana?

Or:

Are neutrinos their own antiparticle?





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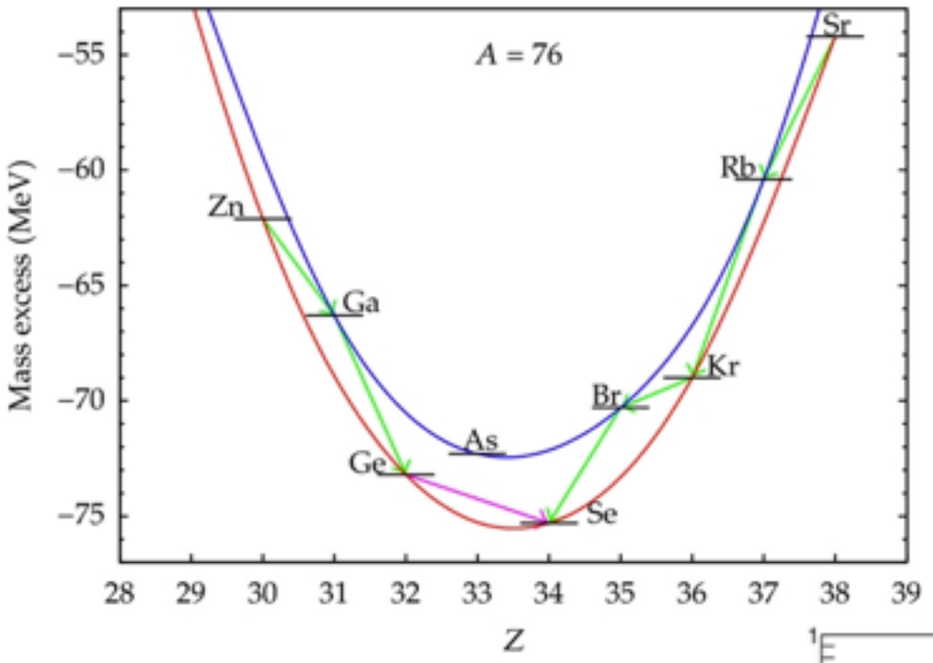

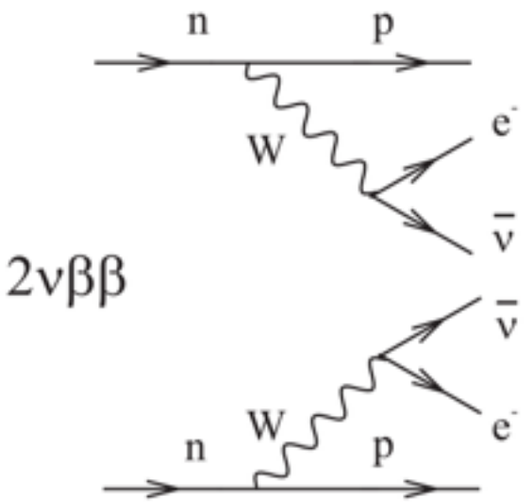

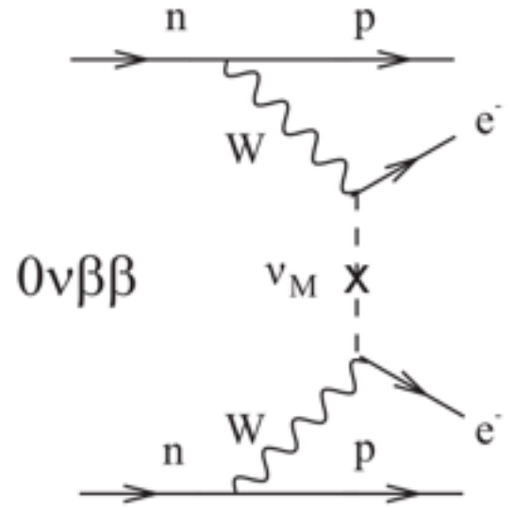

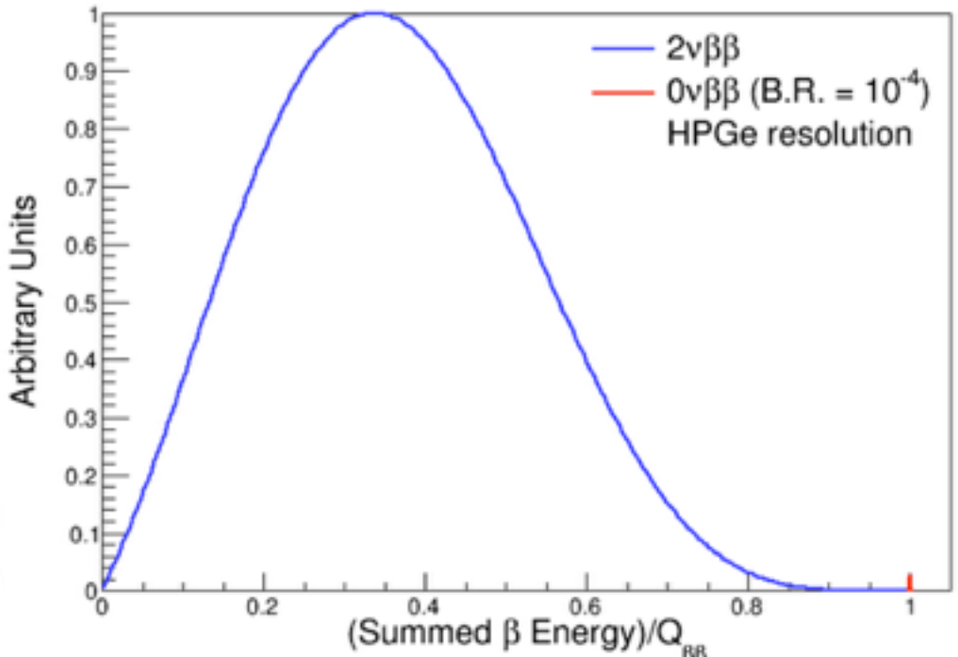

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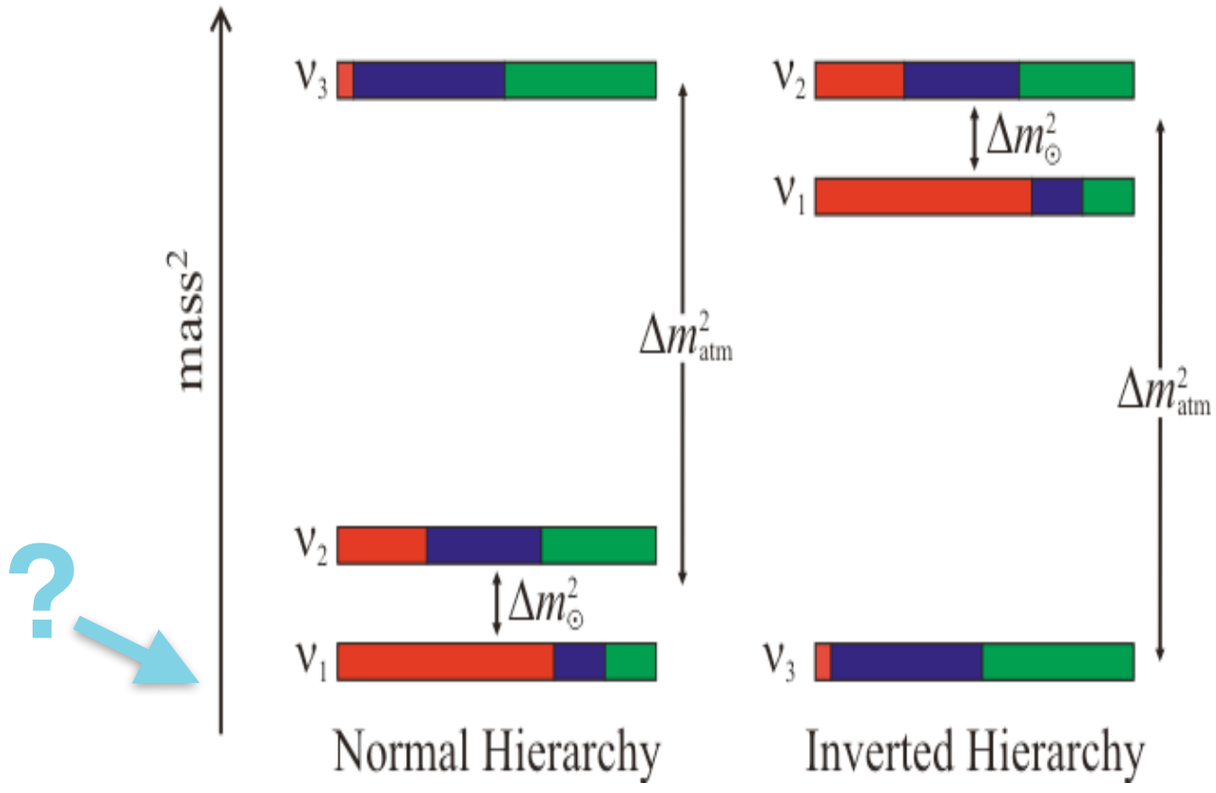
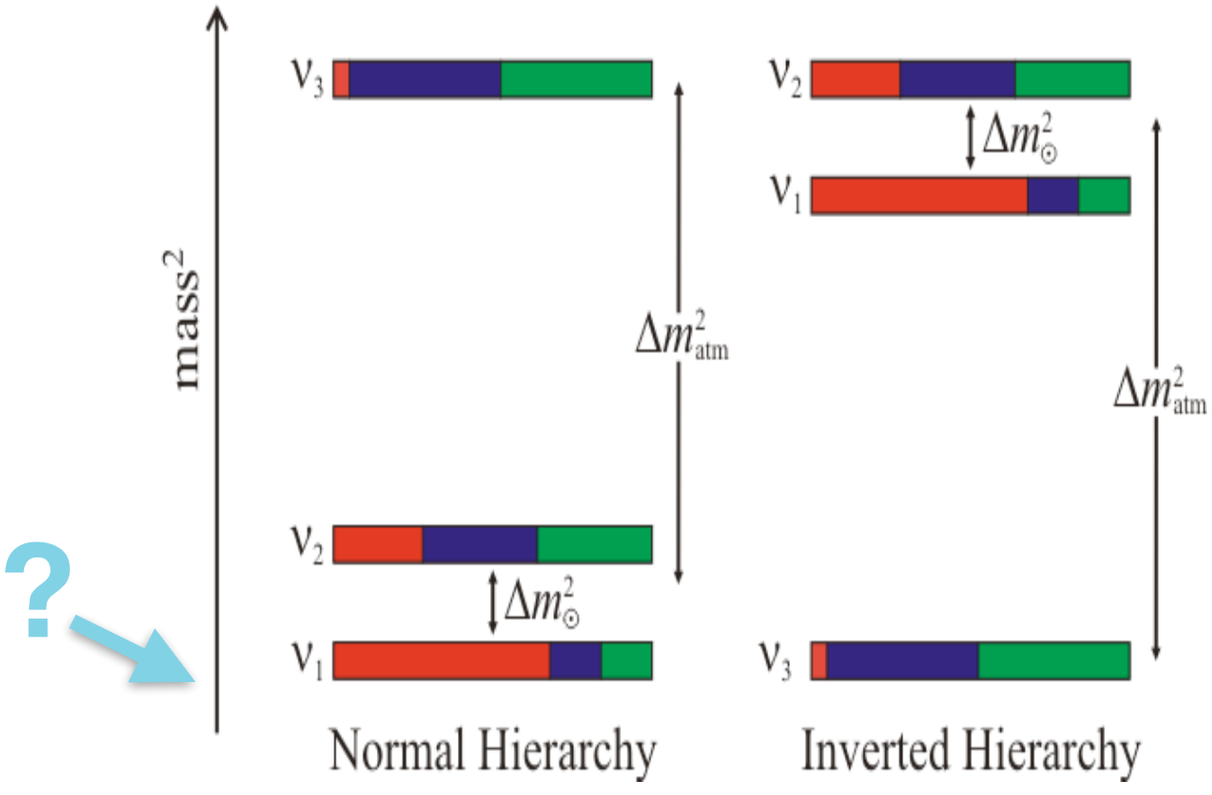
Open questions

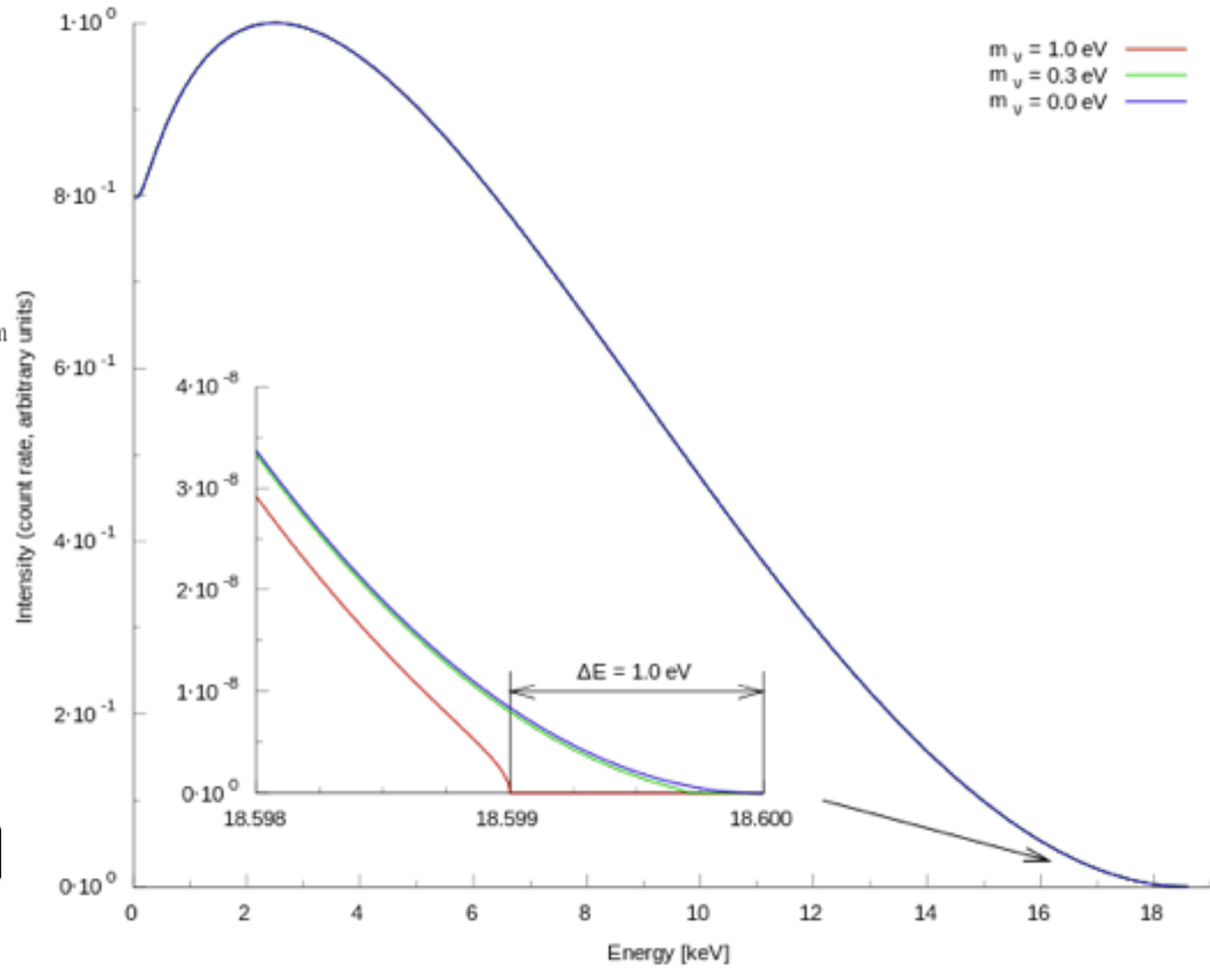
What is the absolute neutrino mass?

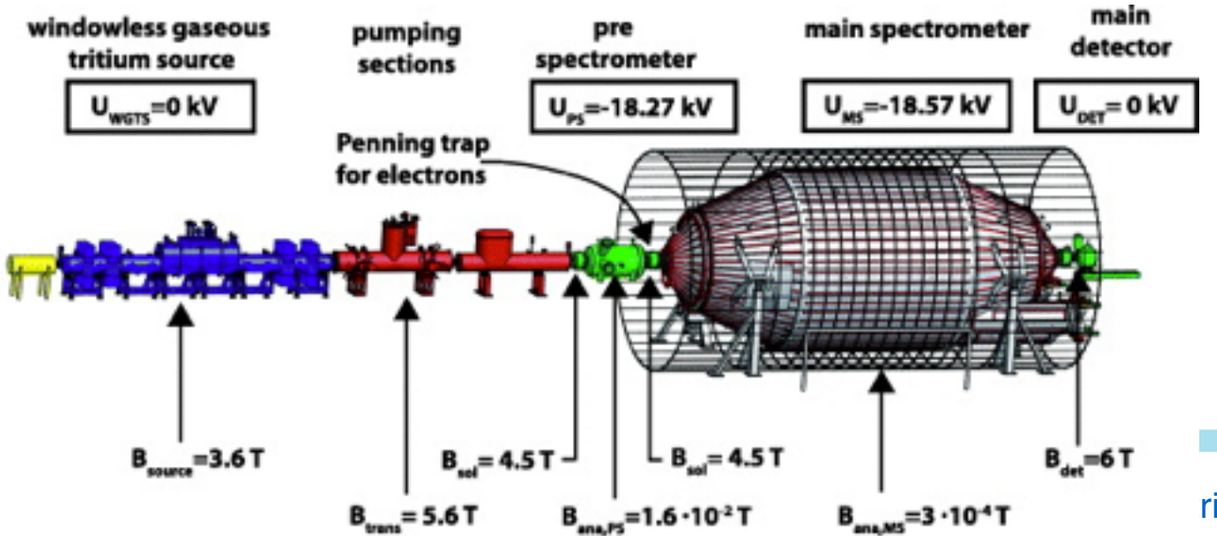


Open questions

What is the absolute neutrino mass?







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Open questions

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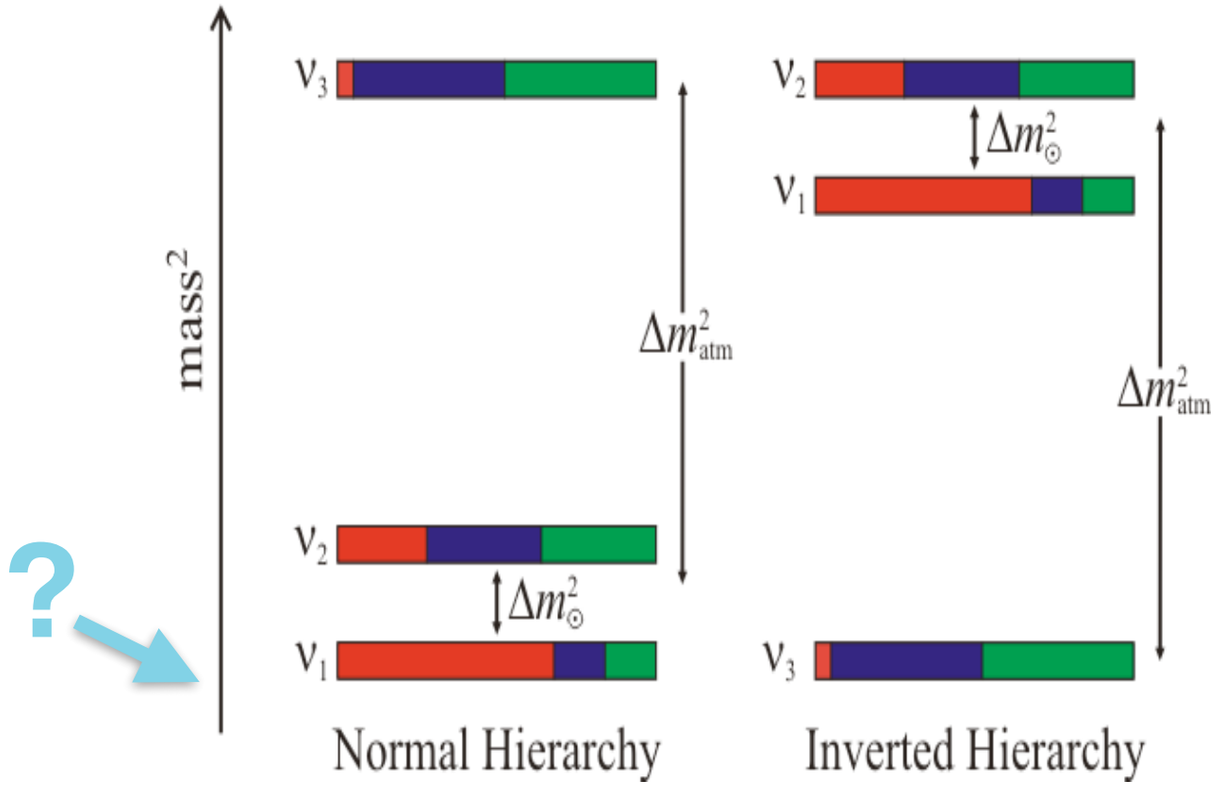
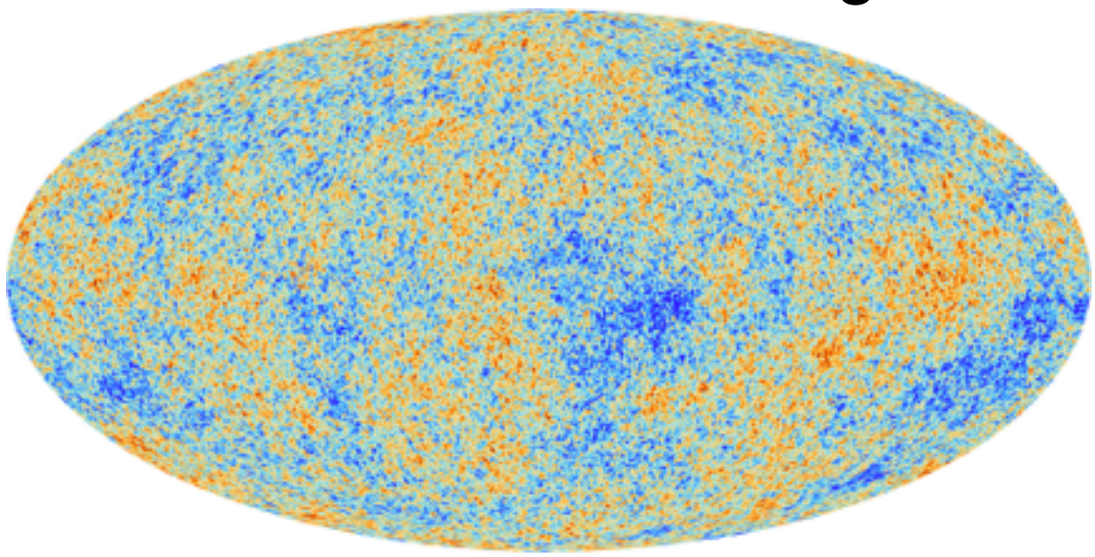


Neutrino masses impacts the cosmic microwave background!



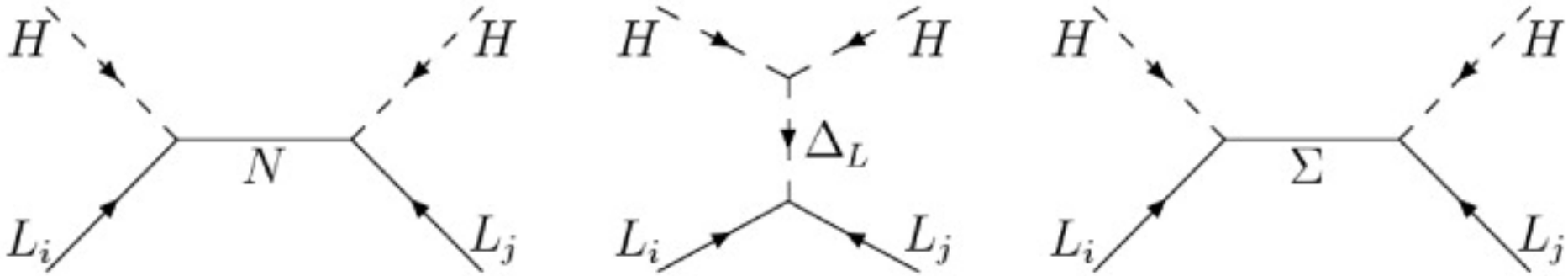
Open questions

What is the mechanism
behind neutrino masses?

Open questions

What is the mechanism
behind neutrino masses?

Seesaw scenarios



Open questions

What is the mechanism
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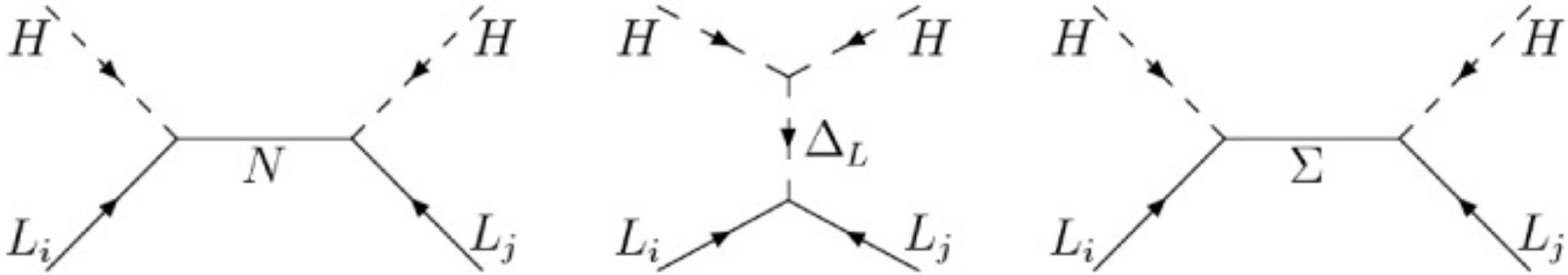
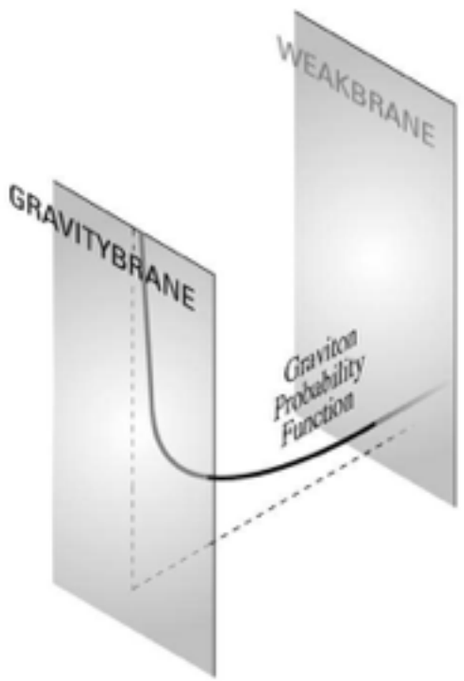
Seesaw scenarios



Extra dimensions



Open questions

What is the mechanism
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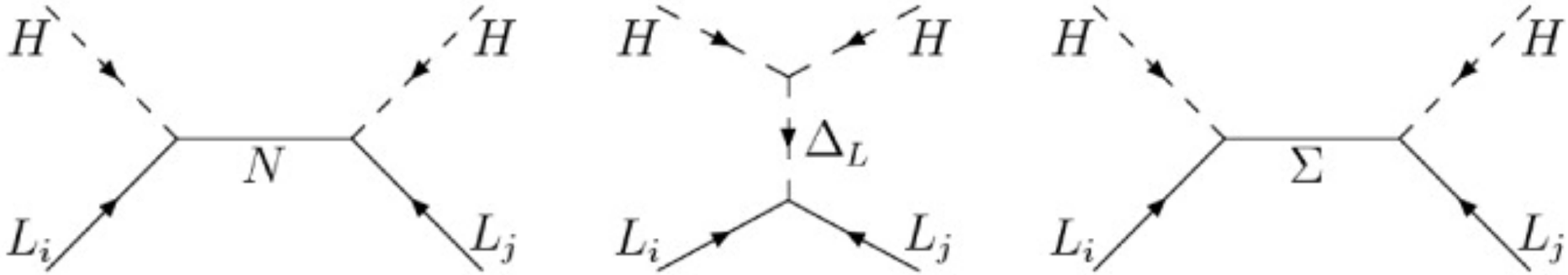
Seesaw scenarios



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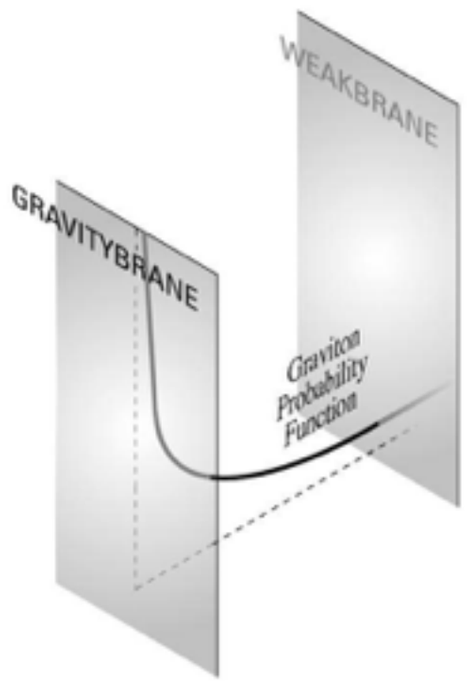
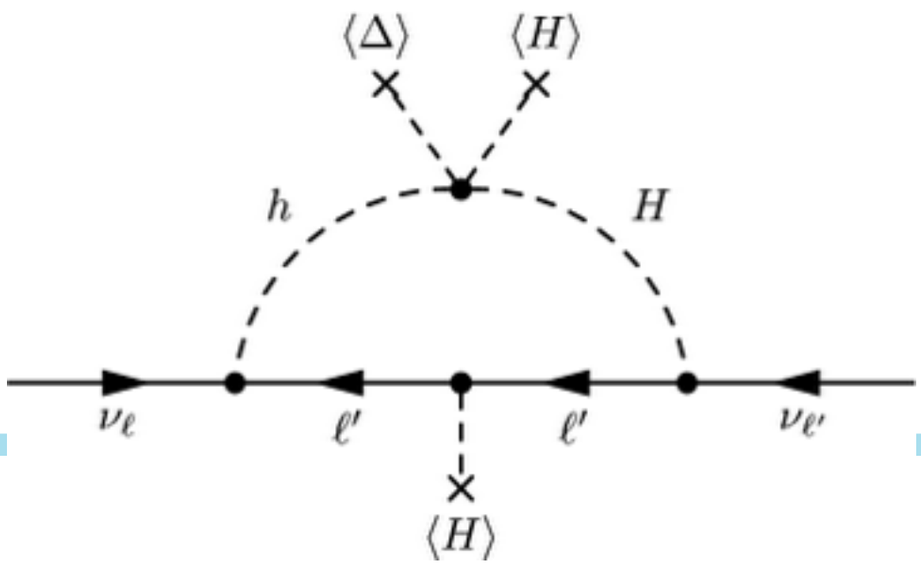


Radiative masses



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Open questions

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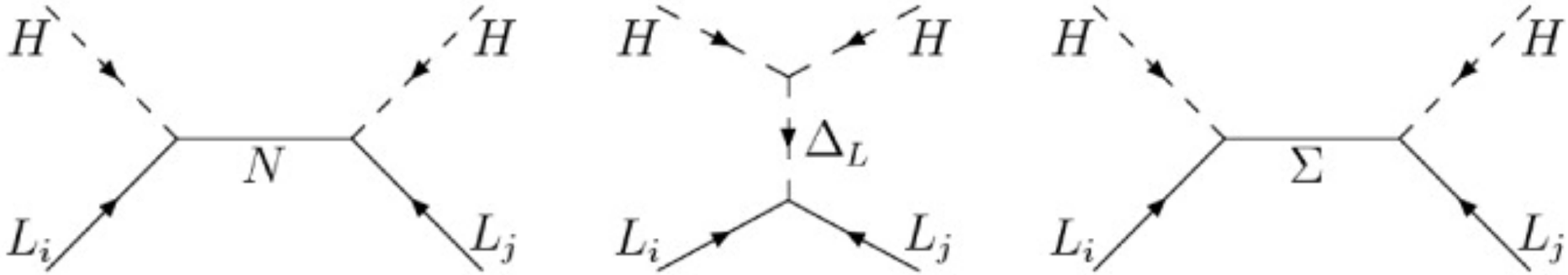
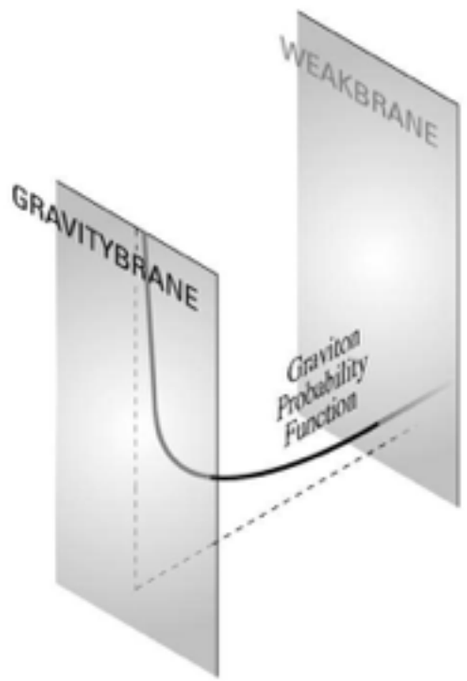
behind neutrino masses?

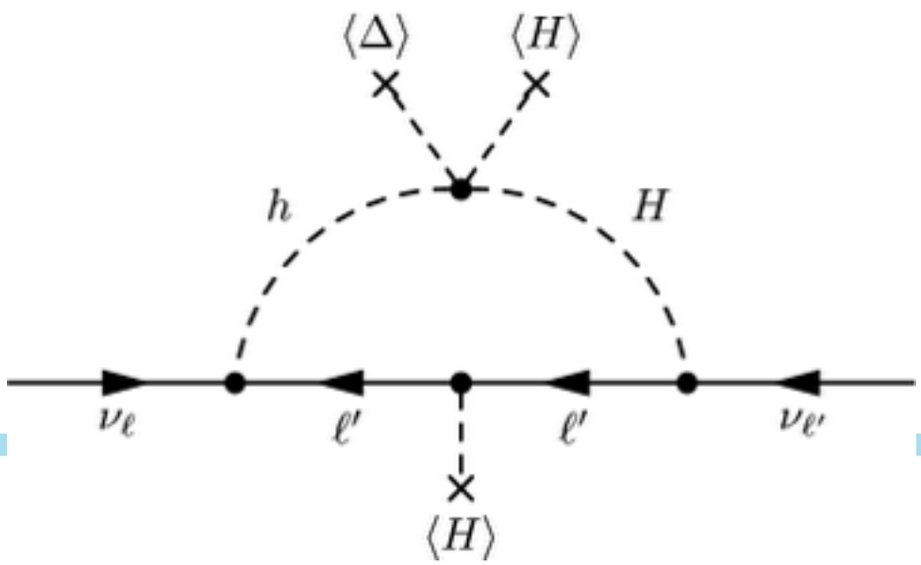
Seesaw scenarios



Extra dimensions



Radiative masses



Fermilab
pmachado@fnal.gov

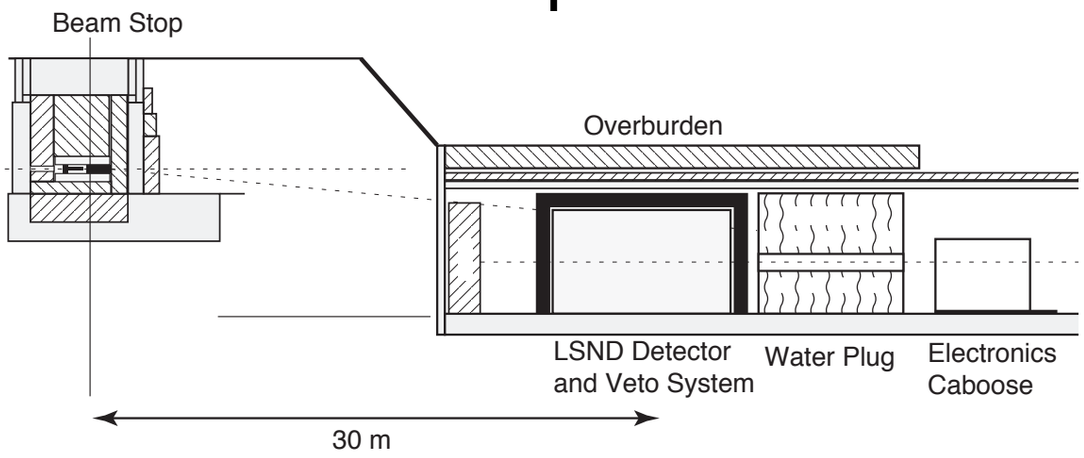
Open questions

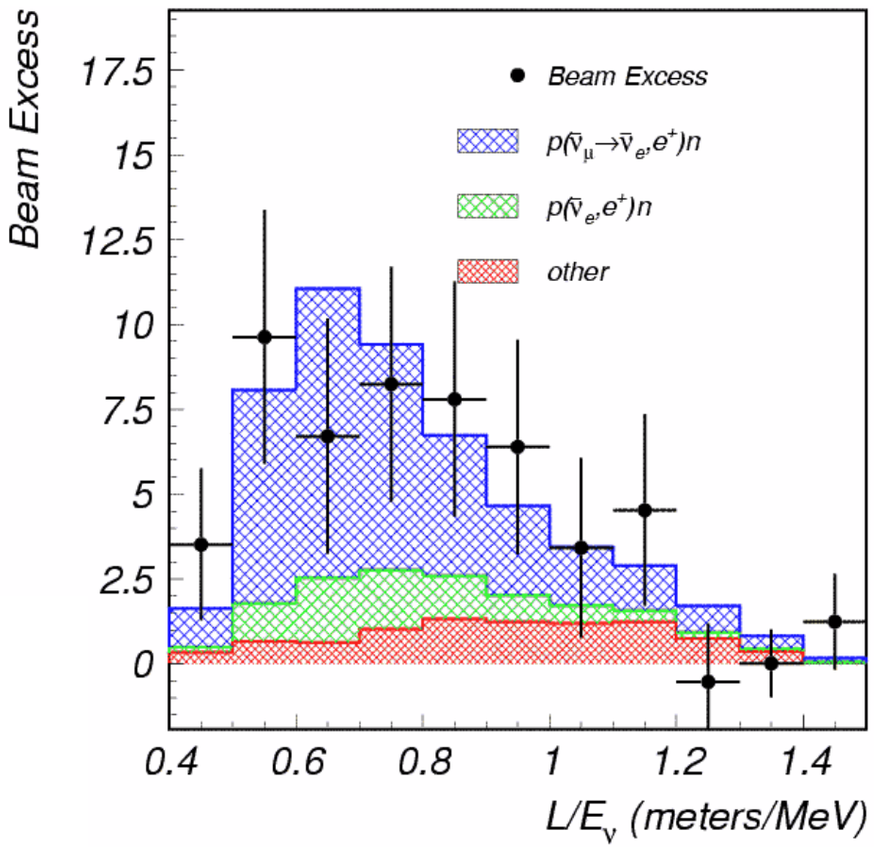
Is there a 4th neutrino (“sterile neutrino”)?

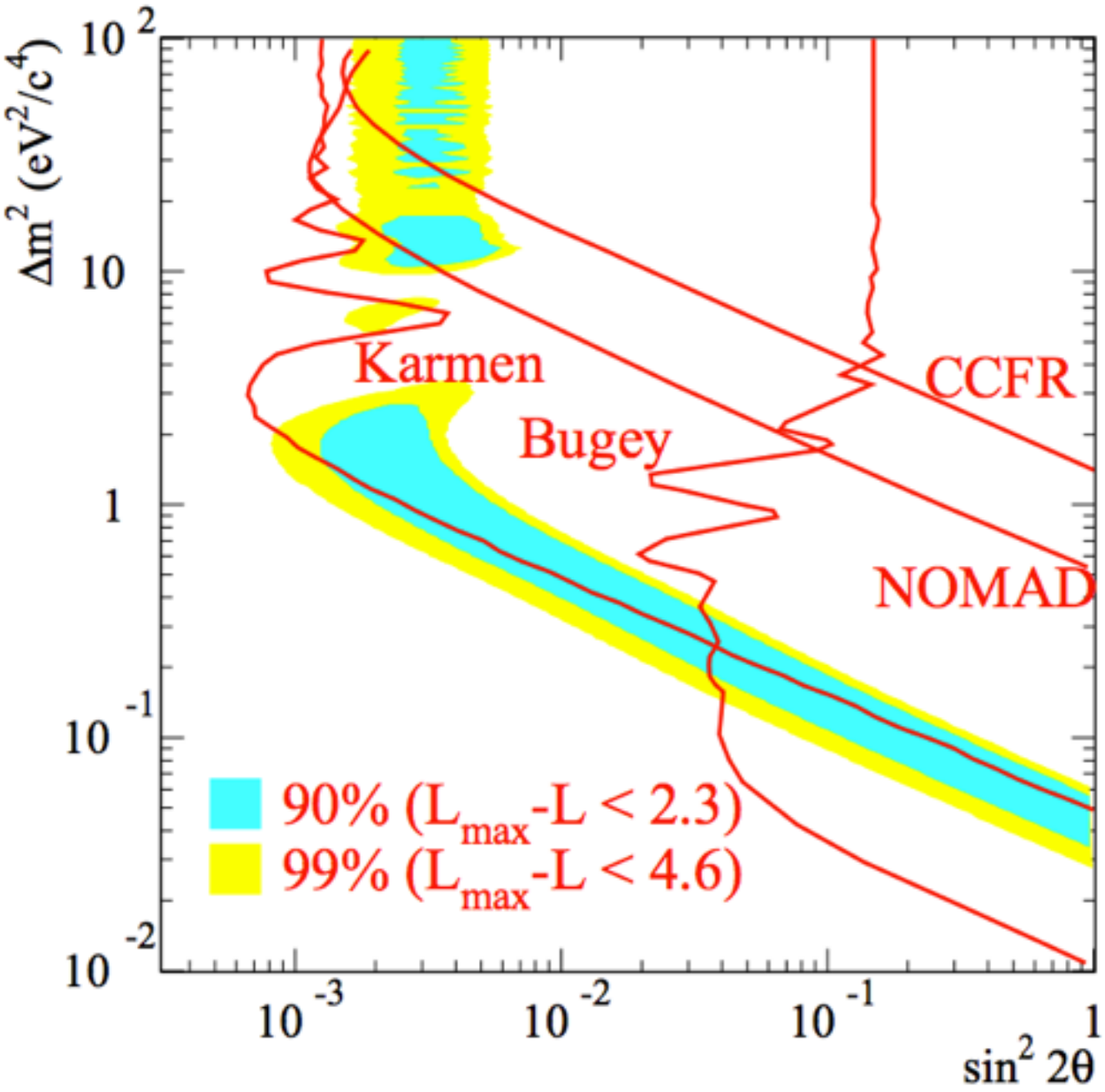
Open questions

Is there a 4th neutrino (“sterile neutrino”)?

LSND experiment



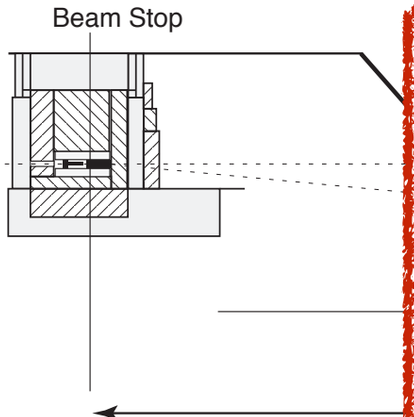




Open questions

Is there a 4th neutrino (“sterile neutrino”)?

LSND experiment

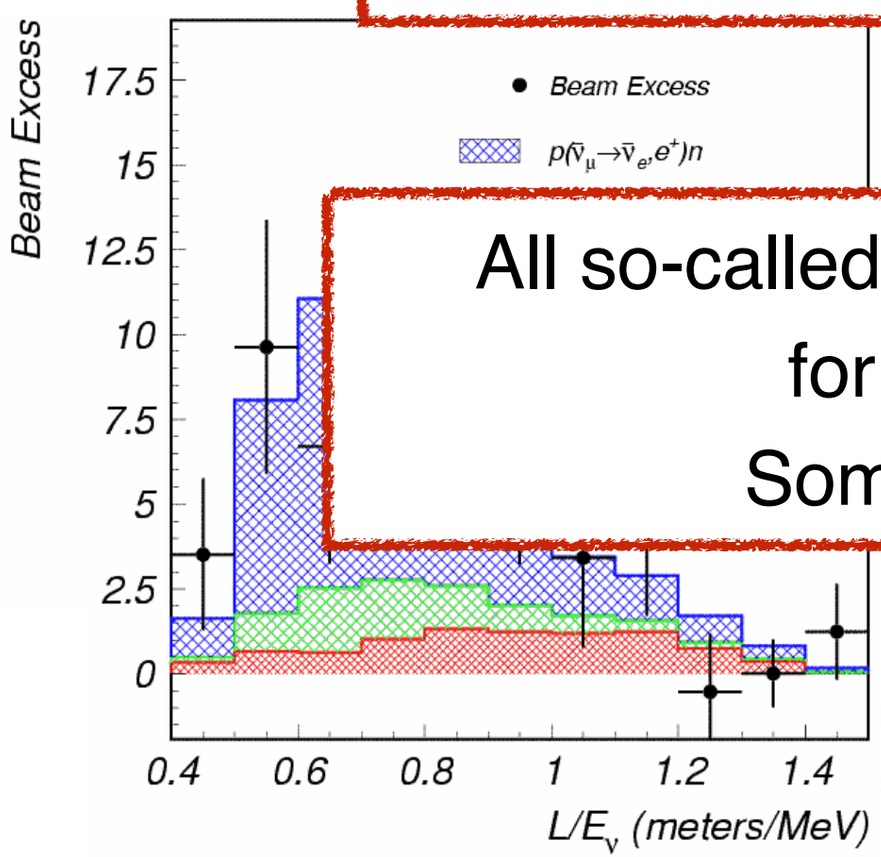


+ MiniBooNE anomaly

+ Reactor neutrino anomaly

+ Gallium anomaly

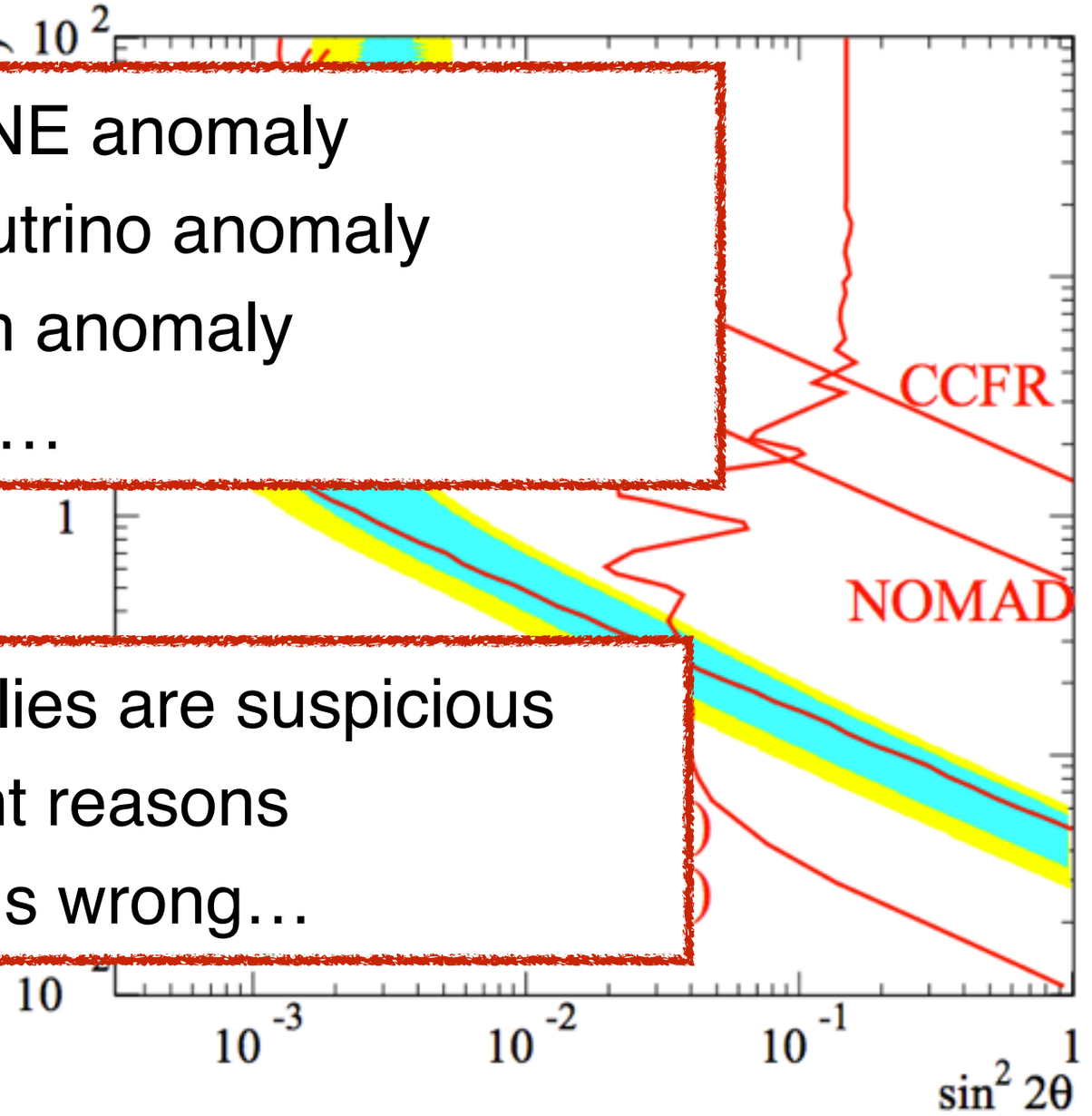
+…



All so-called anomalies are suspicious

for different reasons

Something is wrong…



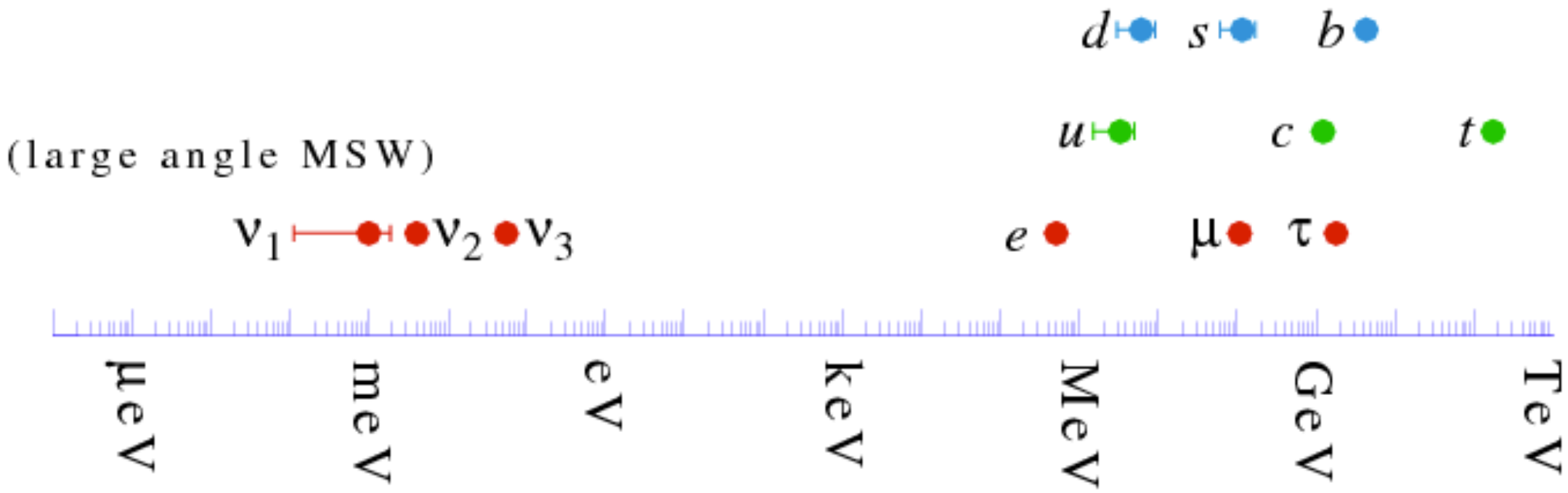
Open questions

Is there a reason behind the masses and mixings?

Also called “the flavor puzzle"

$$V_{\rm CKM} = \begin{pmatrix} 0.9743 & 0.22506 & 0.00357 \\ 0.22492 & 0.97351 & 0.0411 \\ 0.0087 & 0.0403 & 0.99915 \end{pmatrix}$$

$$U_{\rm PMNS} = \begin{pmatrix} 0.795-0.846 & 0.513-0.585 & 0.126-0.178 \\ 0.205-0.543 & 0.416-0.730 & 0.579-0.808 \\ 0.215-0.548 & 0.409-0.725 & 0.567-0.800 \end{pmatrix}$$



Open questions

Neutrino masses go beyond the SM

The neutrino sector is the least known sector of the SM

Why so light? Why so much mixing?

Anomalies in neutrino oscillations

Are neutrinos a portal to new physics?